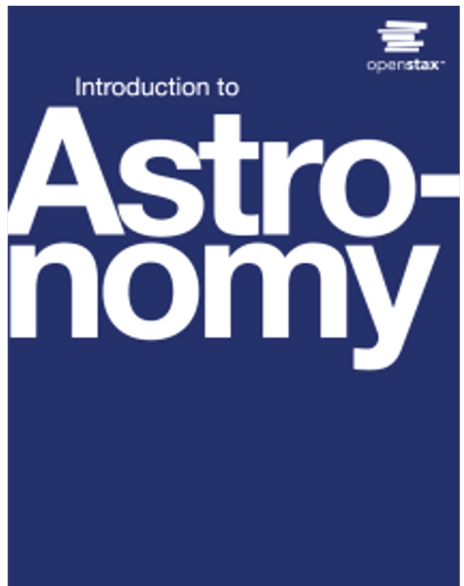
ASTRONOMY

Chapter 15 THE SUN: A GARDEN-VARIETY STAR
Chapter 16 THE SUN: A NUCLEAR POWERHOUSE



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WHAT WE LEARN FROM STUDYING THE SUN APPLIES TO OTHER STARS

All of the thousands of stars you can see at night with the naked-eye, and all of the millions you can see faintly shining in the Milky Way, are suns, similar to ours.

Our galaxy contains 100 billion suns, and most are ordinary stars very similar to our Sun.

So what we learn from studying the Sun also applies to all of these ordinary stars. Since nearly every other star can be seen only as a mere point of light, we can see how important it is to have one star close enough to resolve and study in detail.

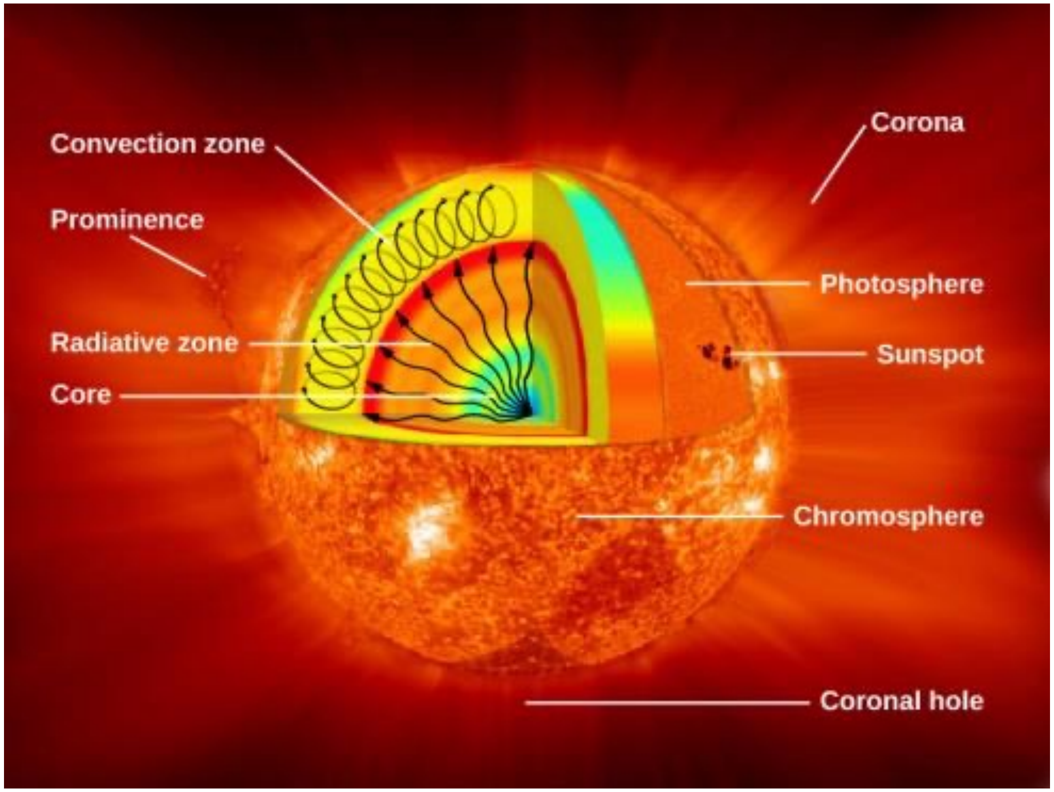
Courtesy Prof Dale Gary

BASIC PROPERTIES OF THE SUN

Table 8.1 Basic Properties of the Sun

Radius (R_{Sun})	696,000 km (about 109 times the radius of Earth)
Mass (M_{Sun})	2×10^{30} kg (about 300,000 times the mass of Earth)
Luminosity (L_{Sun})	3.8×10^{26} watts
Composition (by percentage of mass)	70% hydrogen, 28% helium, 2% heavier elements
Rotation rate	25 days (equator) to 30 days (poles)
Surface temperature	5800 K (average); 4000 K (sunspots)
Core temperature	15 million K

FIGURE 15.4



Parts of the Sun. This illustration shows the different parts of the Sun, from the hot core where the energy is generated through regions where energy is transported outward, first by radiation, then by convection, and then out through the solar atmosphere. The parts of the atmosphere are also labeled the photosphere, chromosphere, and corona. Some typical features in the atmosphere are shown, such as coronal holes and prominences. (credit: modification of work by NASA/Goddard)

SOLAR LUMINOSITY

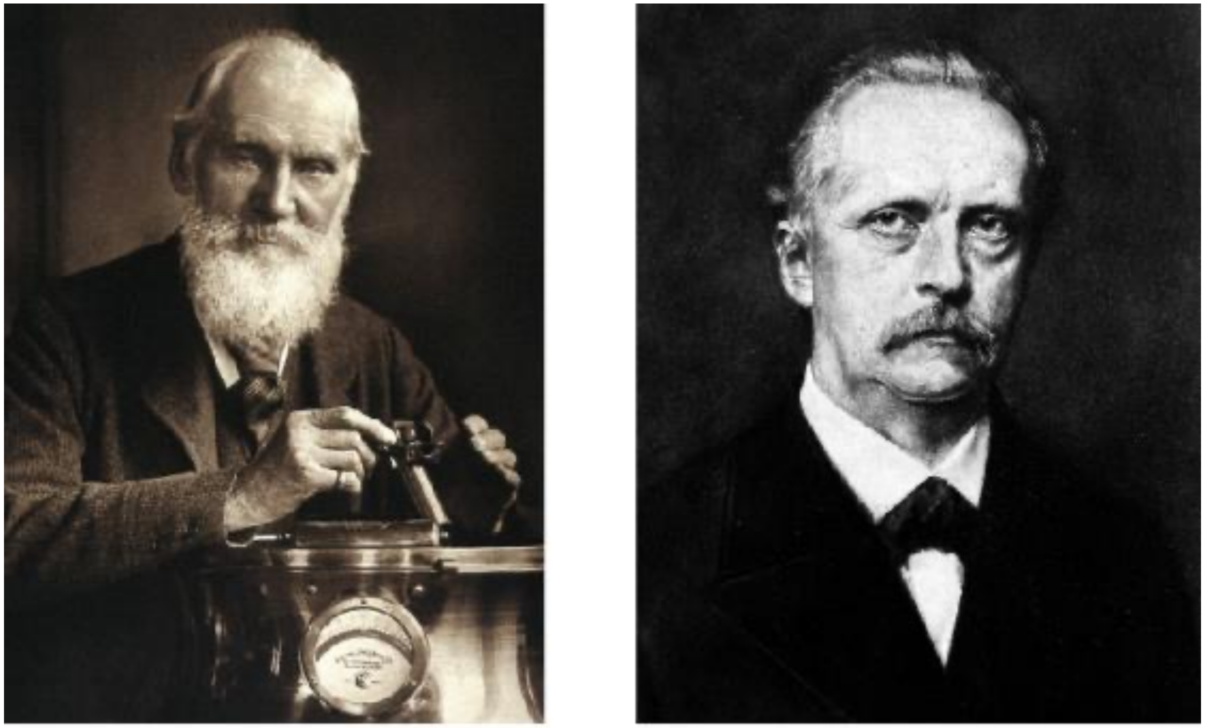
All stars form in basically the same way, and so all stars have the same basic structure.

The power output of the Sun, called the solar luminosity, is constant at 3.8×10^{26} watts.

This is an incredible amount of power--even at the distance of the Earth we receive 1370 watts/m^2, meaning that we could power about 14 light bulbs of 100 W each, for every square meter of area.

Courtesy Prof Dale Gary

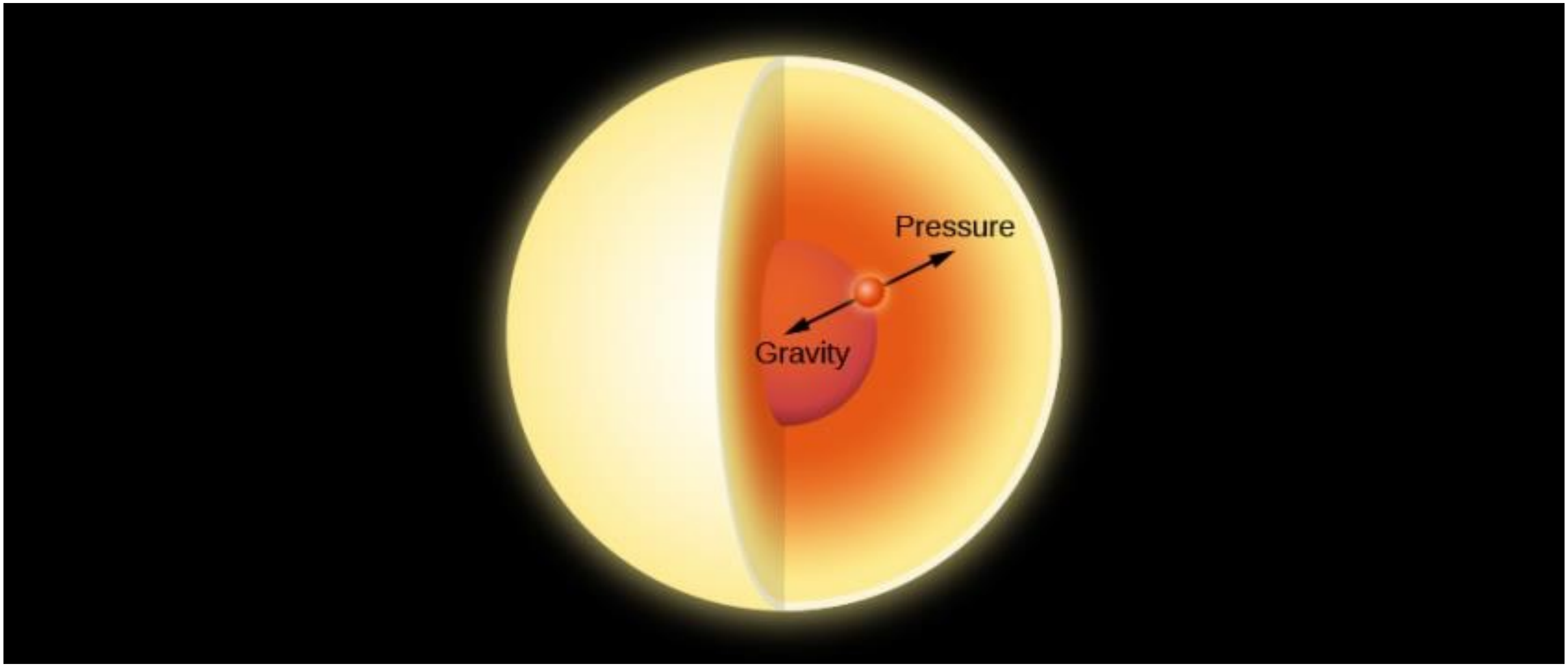
FIGURE 16.2



(a) (b)

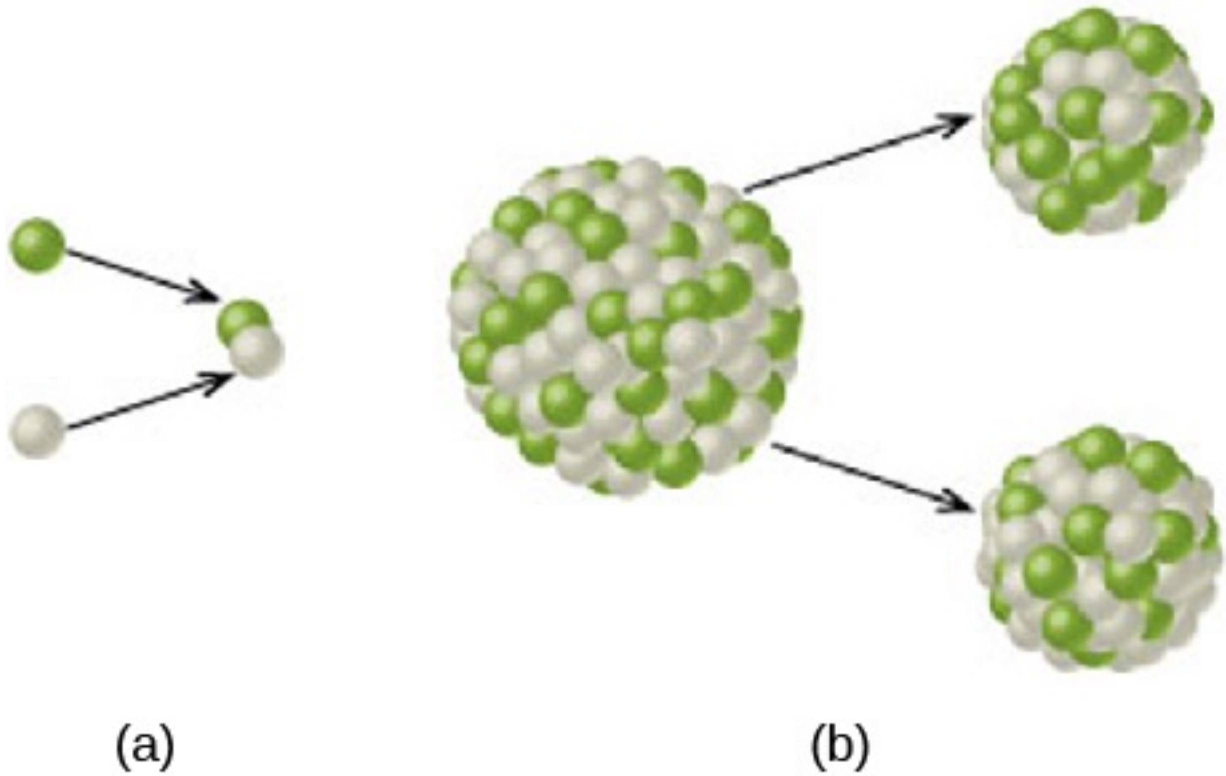
Kelvin (1824–1907) and Helmholtz (1821–1894). (a) British physicist William Thomson (Lord Kelvin) and (b) German scientist Hermann von Helmholtz proposed that the contraction of the Sun under its own gravity might account for its energy. (credit a: modification of work by Wellcome Library, London; credit b: modification of work by Wellcome Library, London)

FIGURE 16.11



Hydrostatic Equilibrium. In the interior of a star, the inward force of gravity is exactly balanced at each point by the outward force of gas pressure.

FIGURE 16.5



Fusion and Fission.

(a) In fusion, light atomic nuclei join together to form a heavier nuclei, releasing energy in the process.

(b) In fission, energy is produced by the breaking up of heavy, complex nuclei into lighter ones.

FUSION AFTER THE BIG BANG

The universe started in the big bang with the simplest of atoms -- mostly hydrogen (just a single proton) and about 10% helium (two protons and two neutrons).

So stars have only these to work with, and to get energy out of them requires fusing them together.

Luckily for stars (and for us), there is plenty of energy to get out of fusing of hydrogen to make helium.

Normally, hydrogen atoms (protons) very strongly resist being pushed together due to the fact that they have the same charge, and like charges repel.

OVERCOMING THE ELECTROMAGNETIC FORCE

The force that keeps them apart is the electromagnetic force.

However, if you can get two protons close enough together, suddenly they are attracted VERY strongly by a new force, called the strong force.

This is the nuclear binding force that holds all atoms together. The trick is to get the two hydrogen atoms close together.

This can be done in the cores of stars because of two properties -- the high pressure, which means that they are close together due to collisions with their neighbors, and the high temperature, which means they are moving very fast and can collide violently.

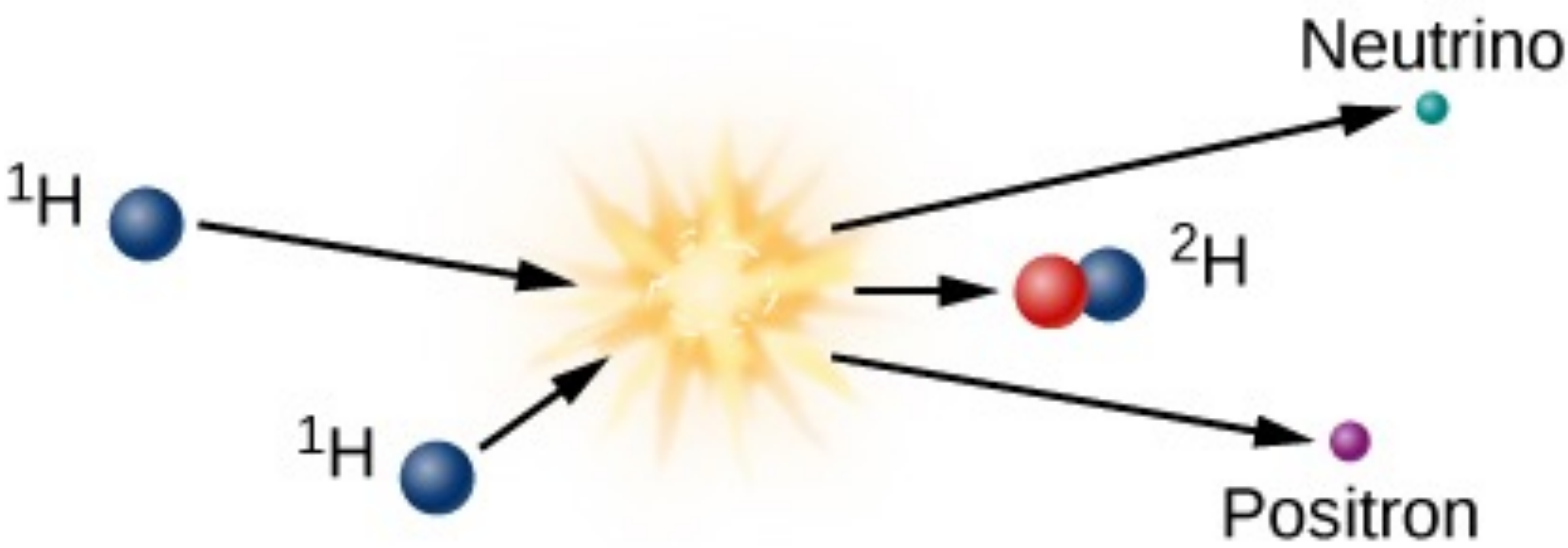
WHEN TWO PROTONS COMBINE…

When two protons combine, you might think you would end up with a light form of helium, but in fact what really happens is that one of the protons spits out its charge in the form of a light particle called positron (this is the antiparticle of the electron).

This is the manifestation of another nuclear force, called the weak force.

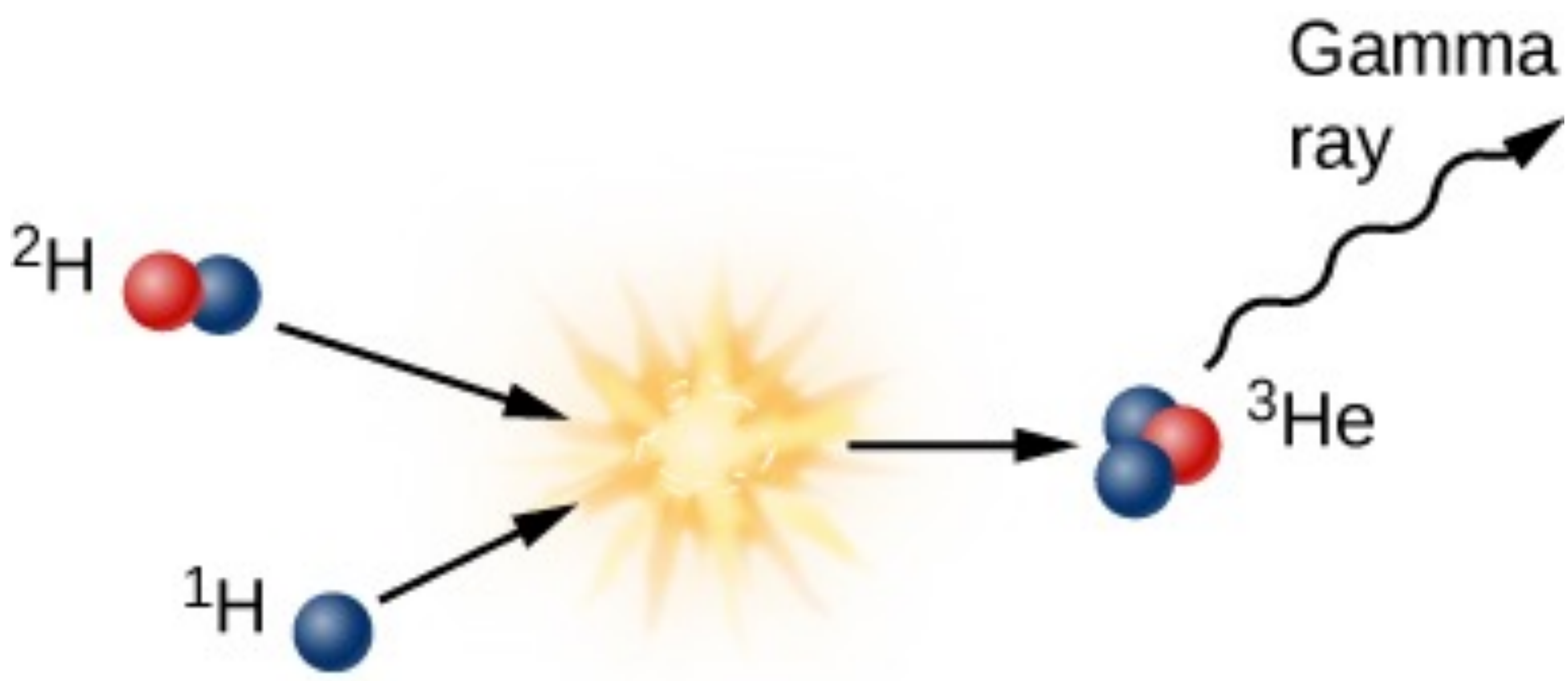
During this decay of the proton, an extremely tiny particle called a neutrino is also produced.

FIGURE 16.6



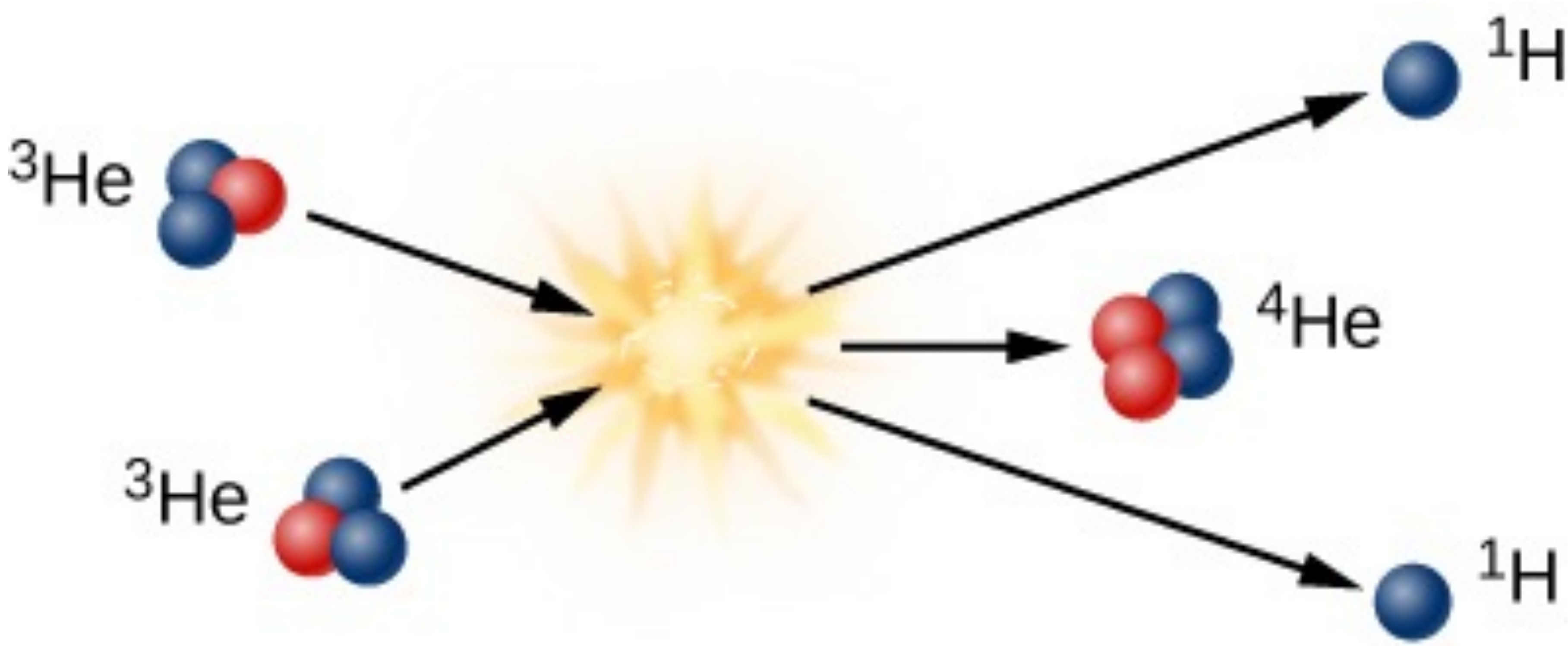
Proton-Proton Chain, Step 1. This is the first step in the process of fusing hydrogen into helium in the Sun. High temperatures are required because this reaction starts with two hydrogen nuclei, which are protons (shown in blue at left) that must overcome electrical repulsion to combine, forming a hydrogen nucleus with a proton and a neutron (shown in red). Note that hydrogen containing one proton and one neutron is given its own name: deuterium. Also produced in this reaction are a positron, which is an antielectron, and an elusive particle named the neutrino.

FIGURE 16.7



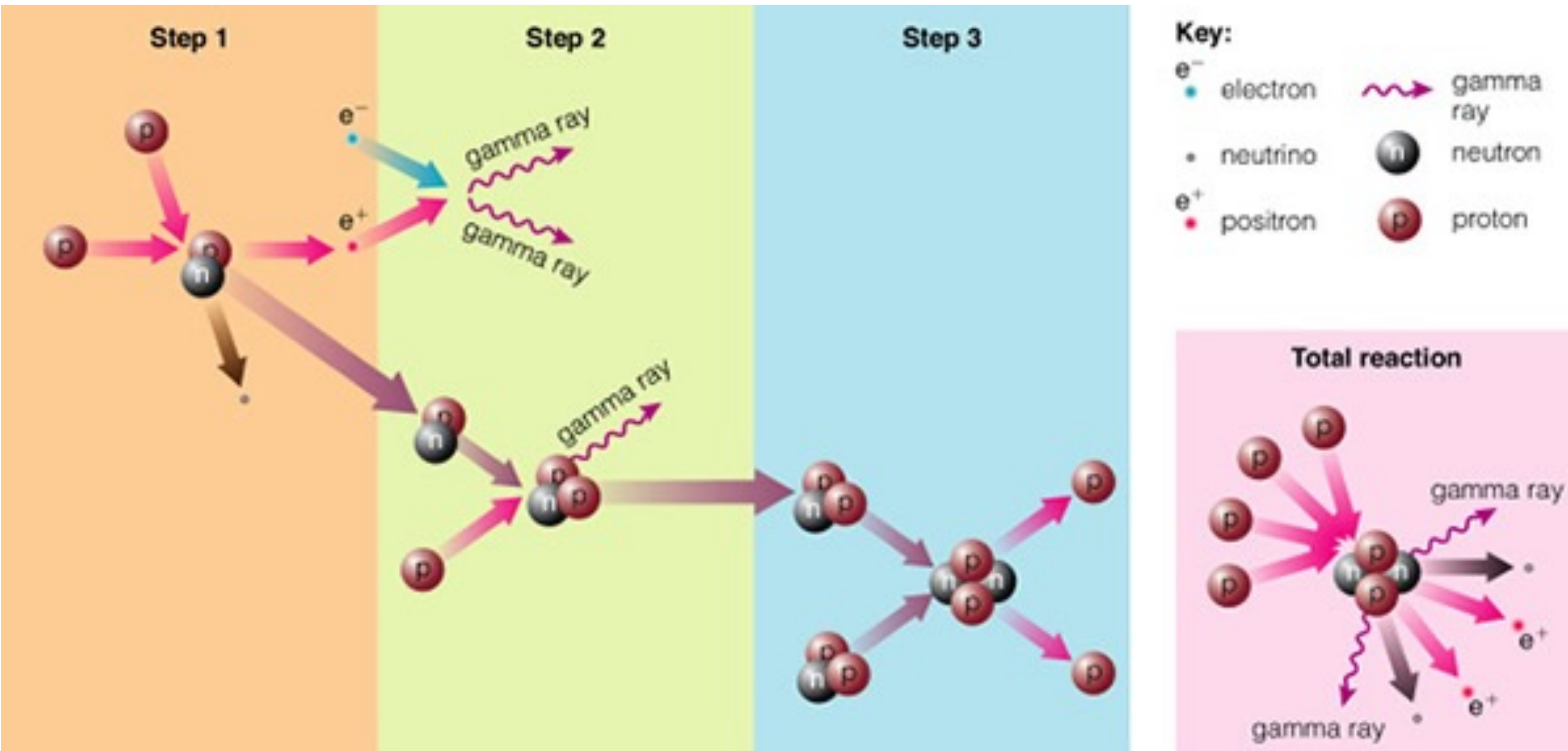
Proton-Proton Chain, Step 2. This is the second step of the proton-proton chain, the fusion reaction that converts hydrogen into helium in the Sun. This step combines one hydrogen nucleus, which is a proton (shown in blue), with the deuterium nucleus from the previous step (shown as a red and blue particle). The product of this is an isotope of helium with two protons (blue) and one neutron (red) and energy in the form of gamma-ray radiation.

FIGURE 16.8



Proton-Proton Chain, Step 3. This is the third step in the fusion of hydrogen into helium in the Sun. Note that the two helium-3 nuclei from the second step (see Figure 16.7) must combine before the third step becomes possible. The two protons that come out of this step have the energy to collide with other protons in the Sun and start step one again.

ULTIMATELY 4 PROTONS COMBINE TO MAKE ONE HELIUM NUCLEUS



HOW LONG DO STARS LIVE?

For the Sun, the reaction rate is fairly slow, so that the hydrogen "fuel" will last about 10 billion years!

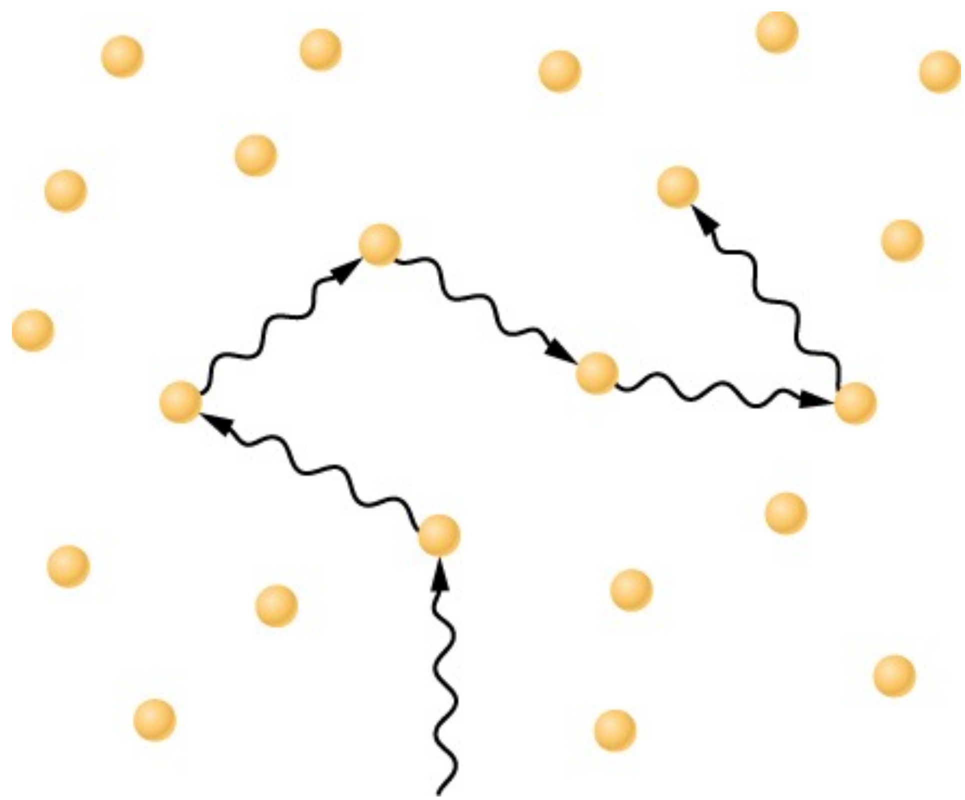
For a more massive star, though, the gravity force is much higher, so the reaction rate has to be higher to balance it.

We will see that more massive stars than the Sun live much shorter lives.

OTHER FUSION PROCESSES

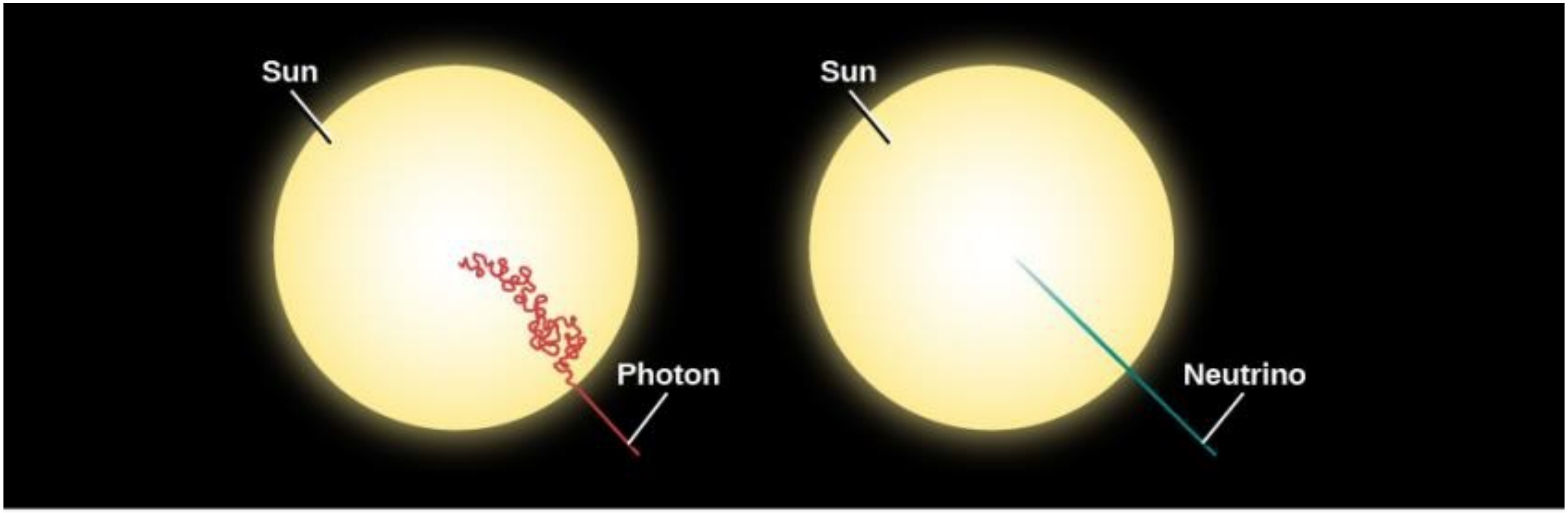
- Hydrogen Fusion, aka, “proton-proton chain”
- Triple Alpha Process
- CNO cycle

FIGURE 16.13



Photons Deep in the Sun. A photon moving through the dense gases in the solar interior travels only a short distance before it interacts with one of the surrounding atoms. The photon usually has a lower energy after each interaction and may then travel in any random direction.

FIGURE 16.14



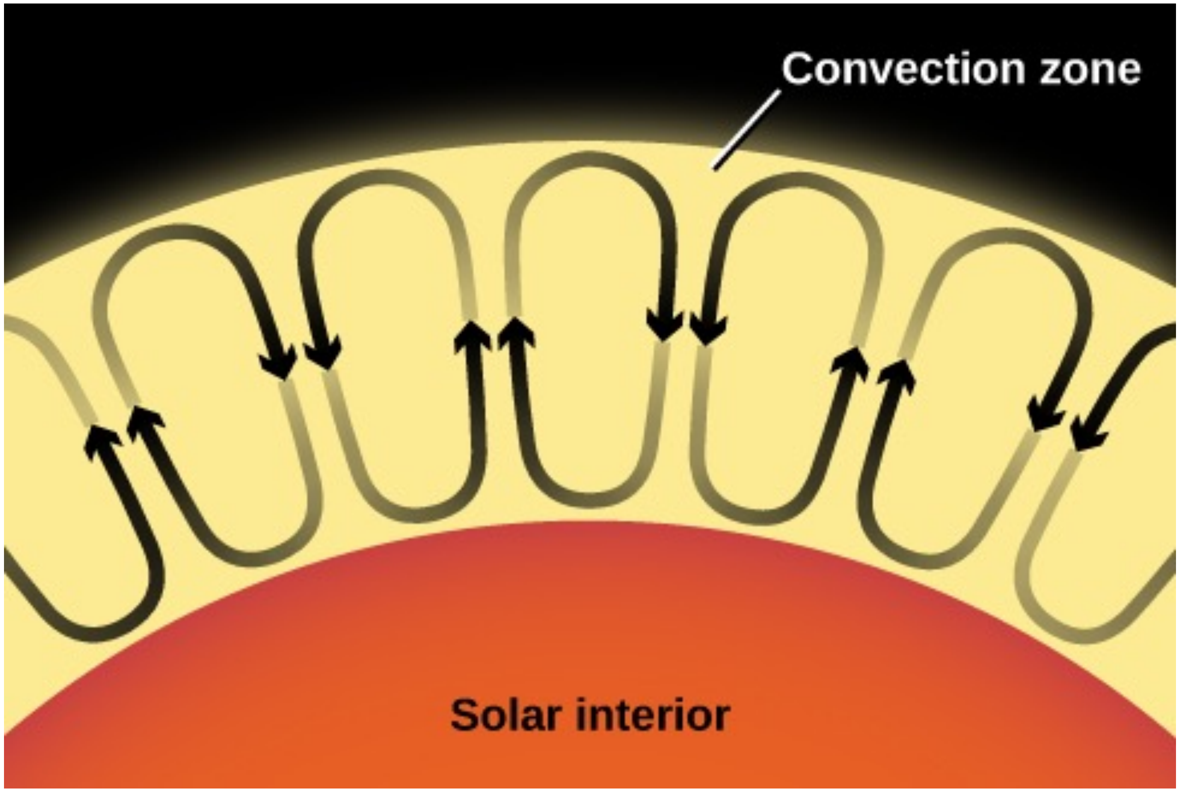
(a) (b)

Photon and Neutrino Paths in the Sun.

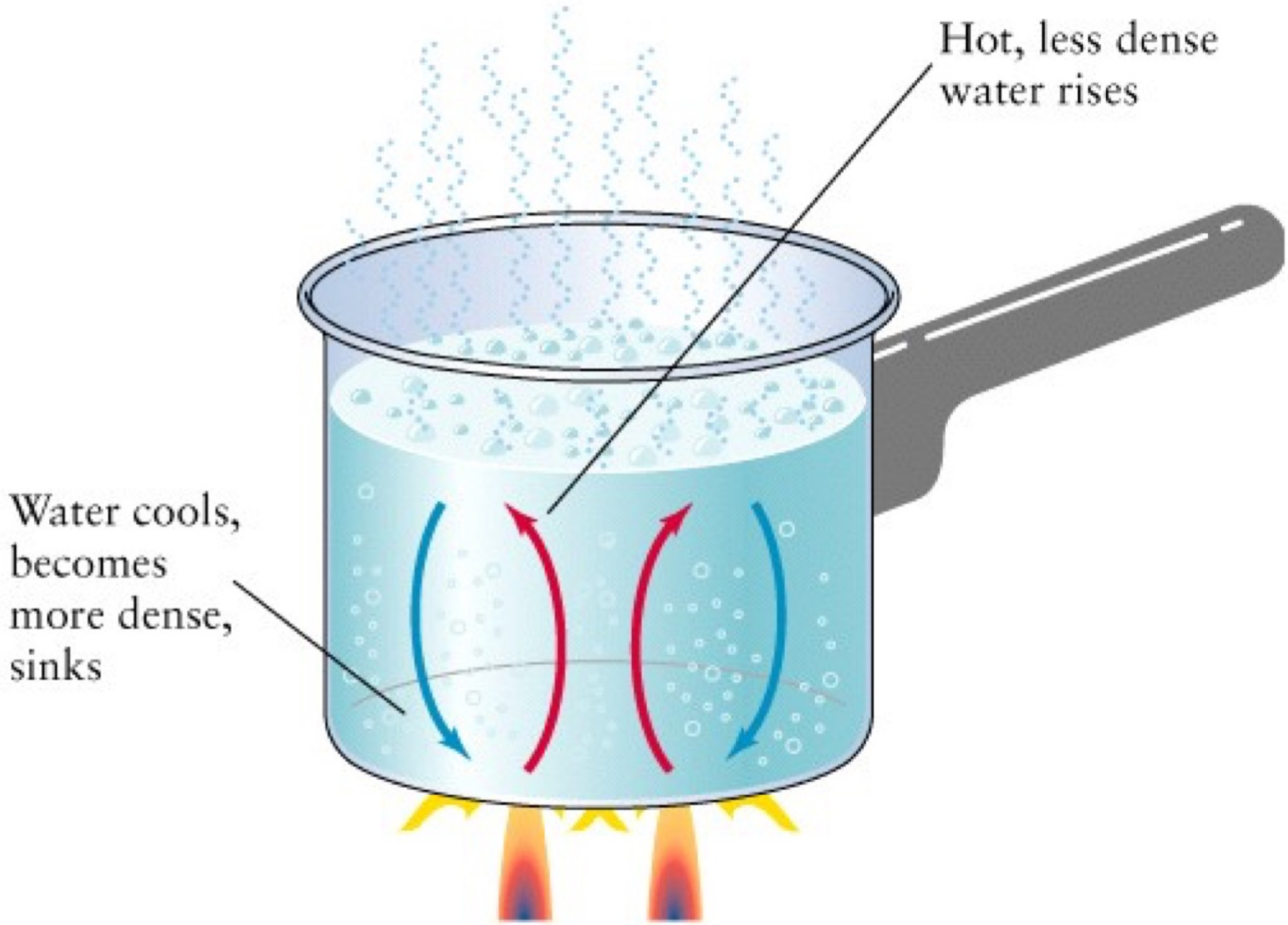
(a) Because photons generated by fusion reactions in the solar interior travel only a short distance before being absorbed or scattered by atoms and sent off in random directions, estimates are that it takes between 100,000 and 1,000,000 years for energy to make its way from the center of the Sun to its surface.

(b) In contrast, neutrinos do not interact with matter but traverse straight through the Sun at the speed of light, reaching the surface in only a little more than 2 seconds.

FIGURE 16.12



Convection. Rising convection currents carry heat from the Sun’s interior to its surface, whereas cooler material sinks downward. Of course, nothing in a real star is as simple as diagrams in textbooks suggest.


Hot, less dense
water rises
Water cools,
becomes
more dense,
sinks

Solar Surface

Photosphere: "Surface of the Sun" (What does that mean?)

Temperature: ~5800 K

Granulation: Top of convective cells

Helioseismology => solar vibrations of p-modes (~5-15min) and g-modes (~1 month)

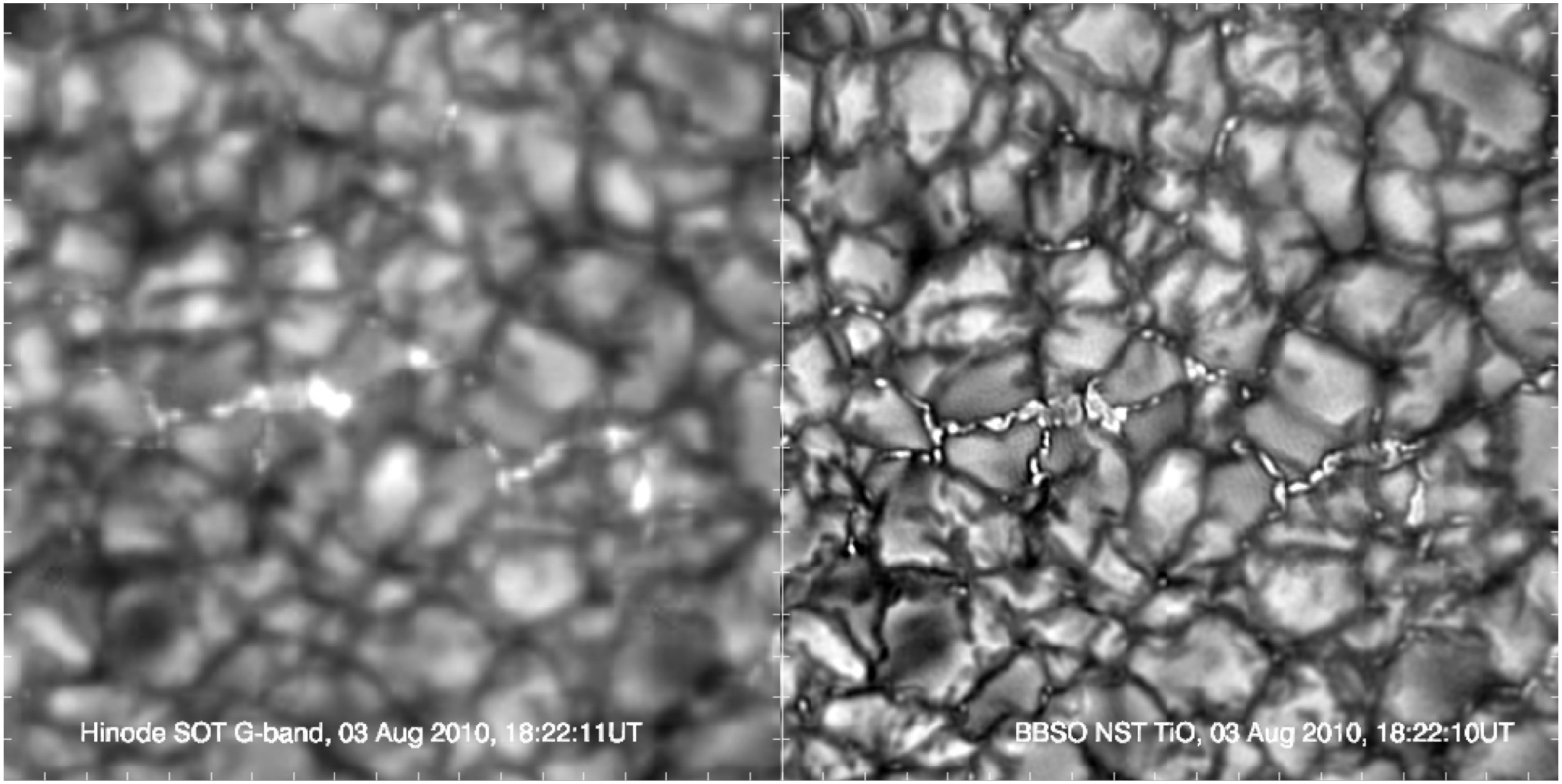
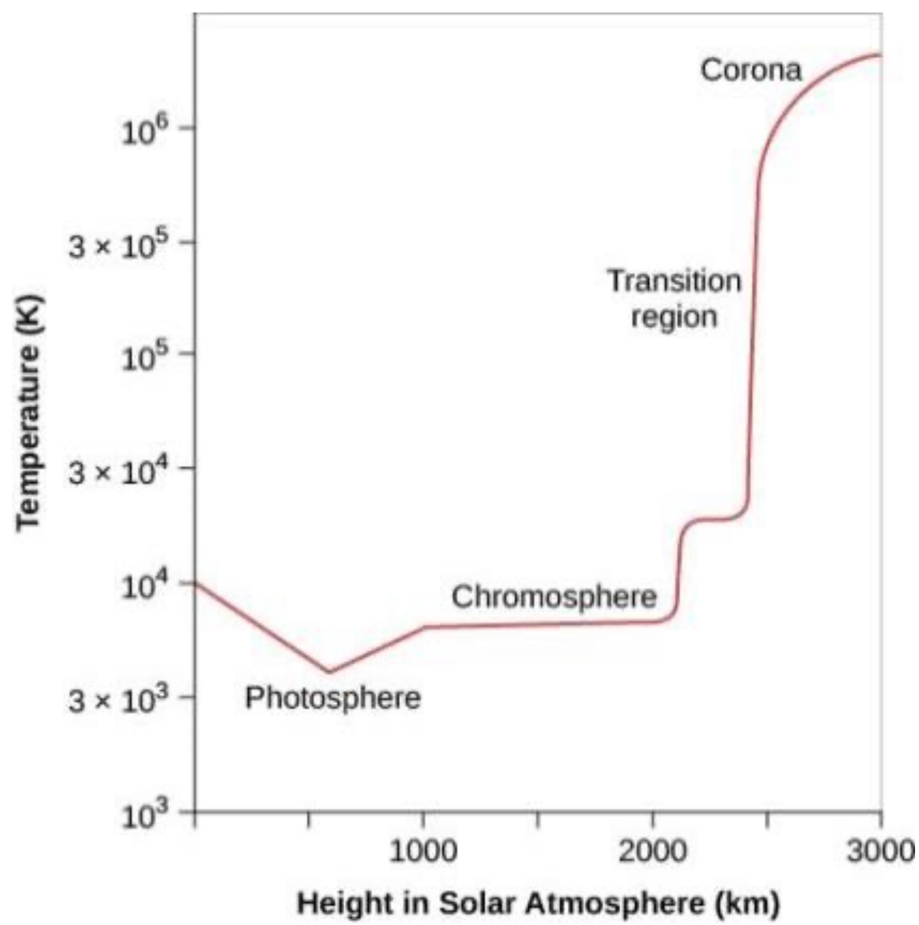


FIGURE 15.8

Temperatures in the Solar Atmosphere. On this graph, temperature is shown increasing upward, and height above the photosphere is shown increasing to the right. Note the very rapid increase in temperature over a very short distance in the transition region between the chromosphere and the corona.

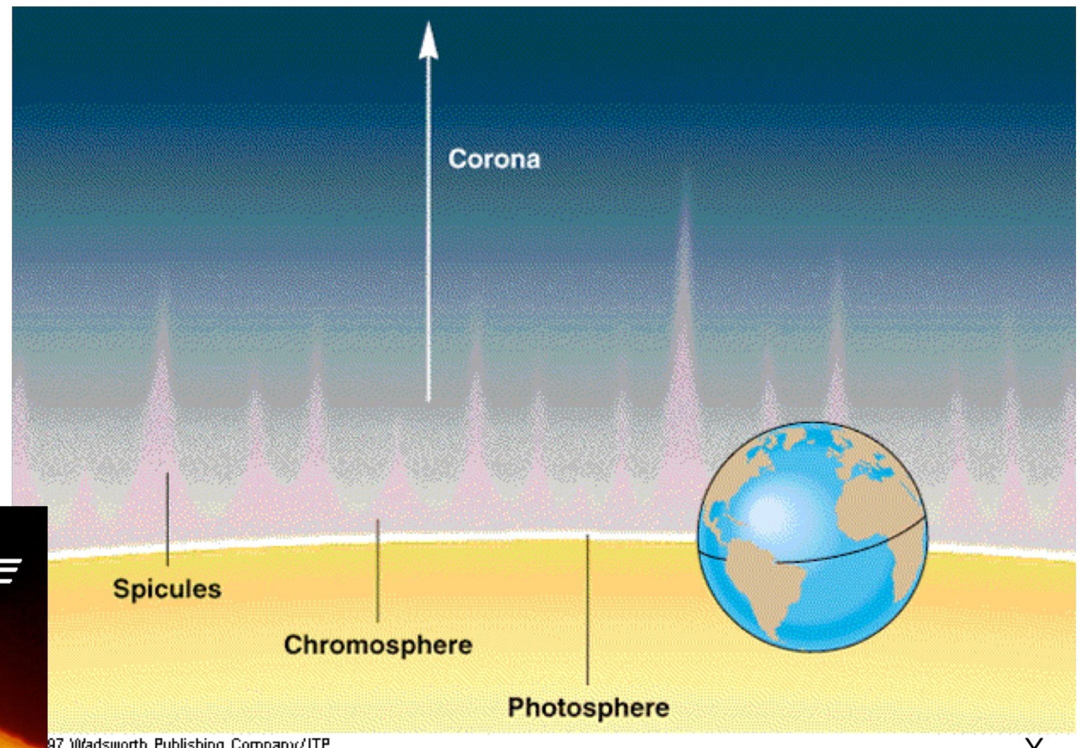


Chromosphere: "Pinkish color", 7,000 K-15,000 K

Spicules (jets of gas that shoot upwards in cylindrical form)

- ~700 km across
- ~7000 km tall
- Occur every 5-15 min
- 1/2 million present at any give time

They are matter ejected from granules



X

Corona: Crown, ghostly white halo
Very hot (what is hot?)... Nobody really knows why
"hot"= few particles with very high velocities/energies

Streamers, long windy-like trails of material extending outward
(can see due to collisions and brightening)

Coronal holes: regions where no streamers seem to exist
(fast moving particles moving quickly outwards)

Supported by magnetic fields extending out into space, called the "solar wind"

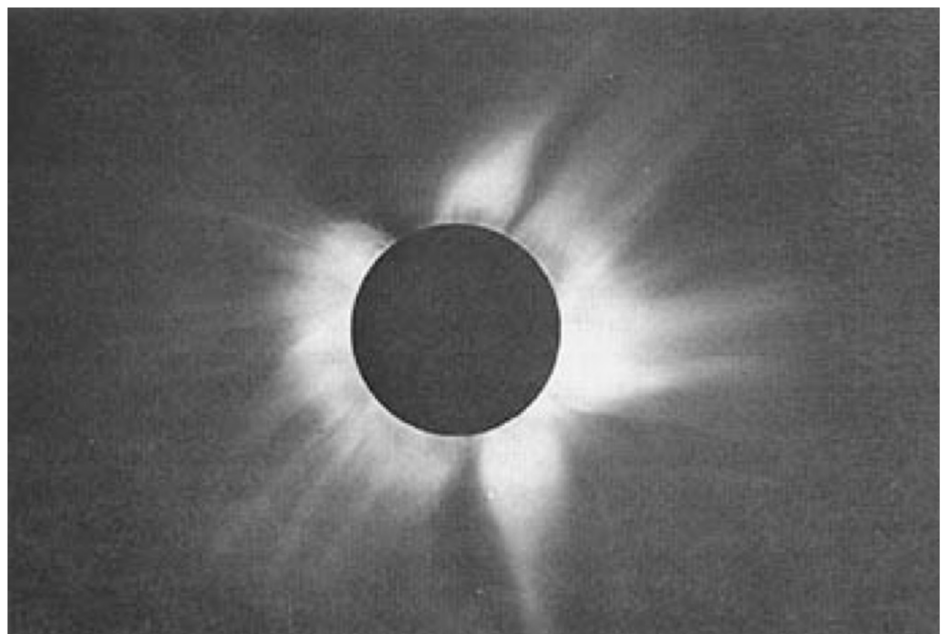
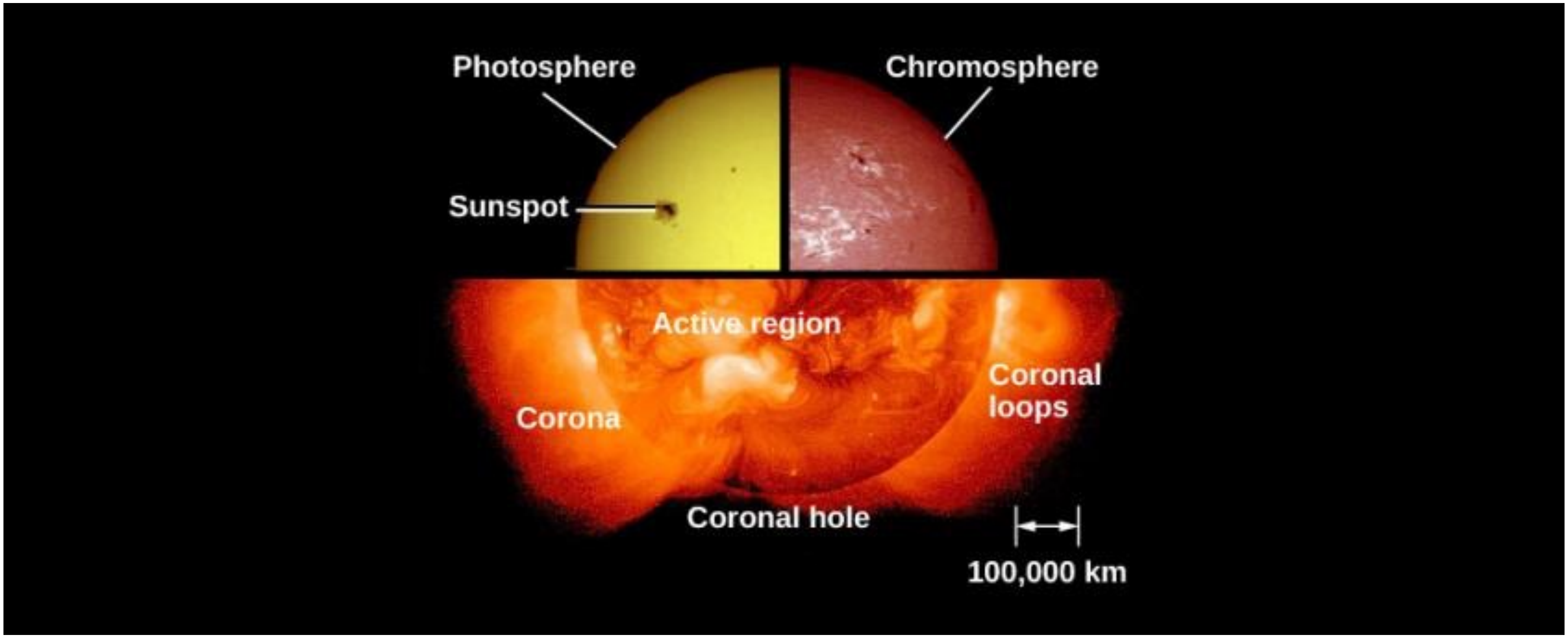
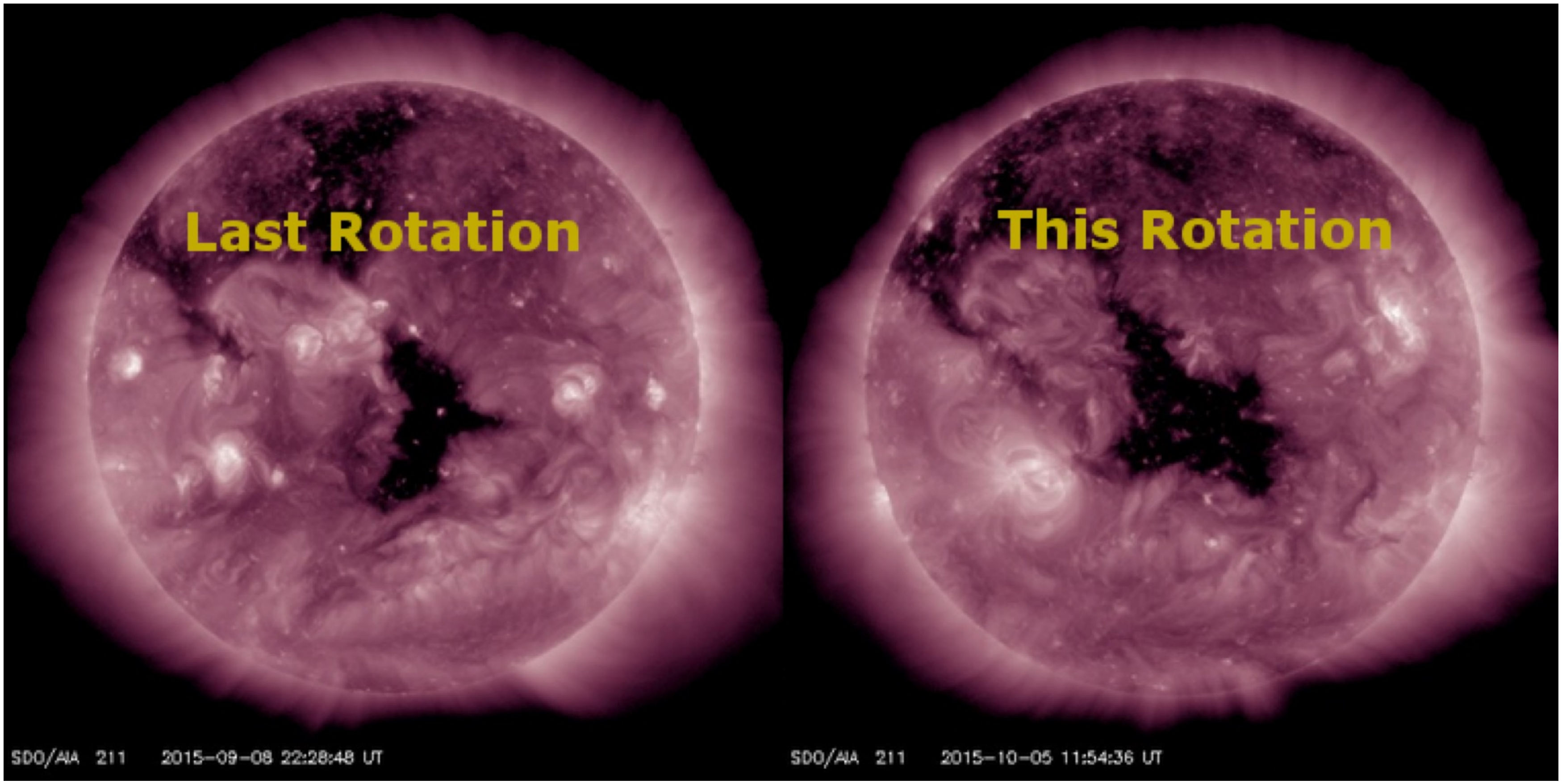


FIGURE 15.7



The Sun's Atmosphere. Composite image showing the three components of the solar atmosphere: the photosphere or surface of the Sun taken in ordinary light; the chromosphere, imaged in the light of the strong red spectral line of hydrogen (H-alpha); and the corona as seen with X-rays. (credit: modification of work by NASA)



Last Rotation
This Rotation
SDO/AIA 211 2015-09-08 22:28:48 UT
SDO/AIA 211 2015-10-05 11:54:36 UT

The Sun-Active Periods

What is "Active?"

The sun emits increased amounts of EM wave energy and radiation

What causes "activity?"

Emerging magnetic field line loops, likely sourced in the convective region, interacting with the nominal solar magnetic field.

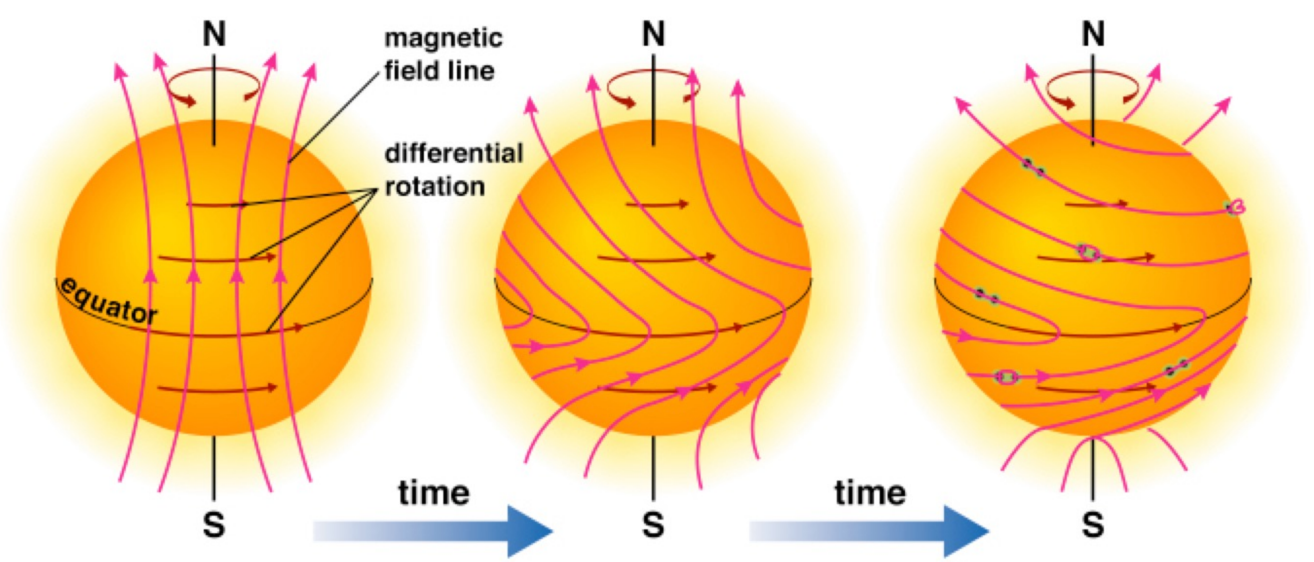
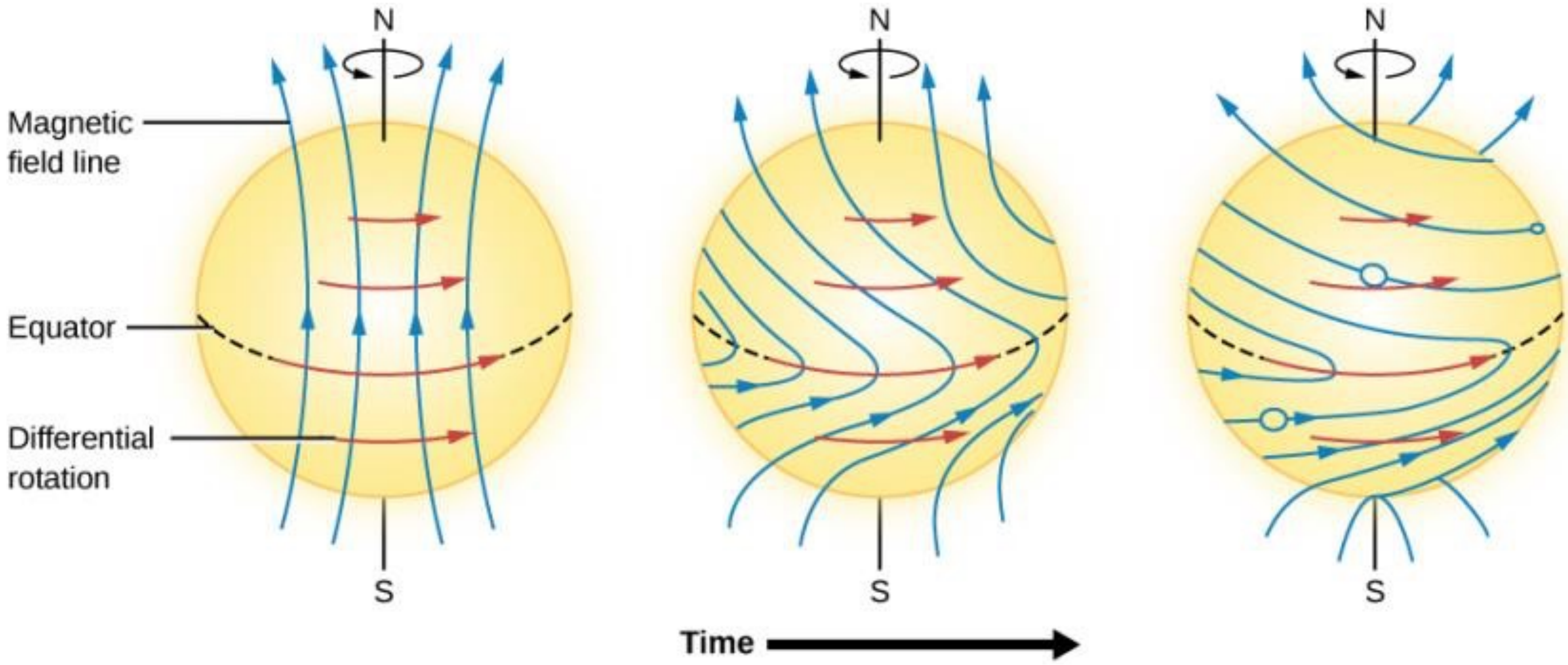
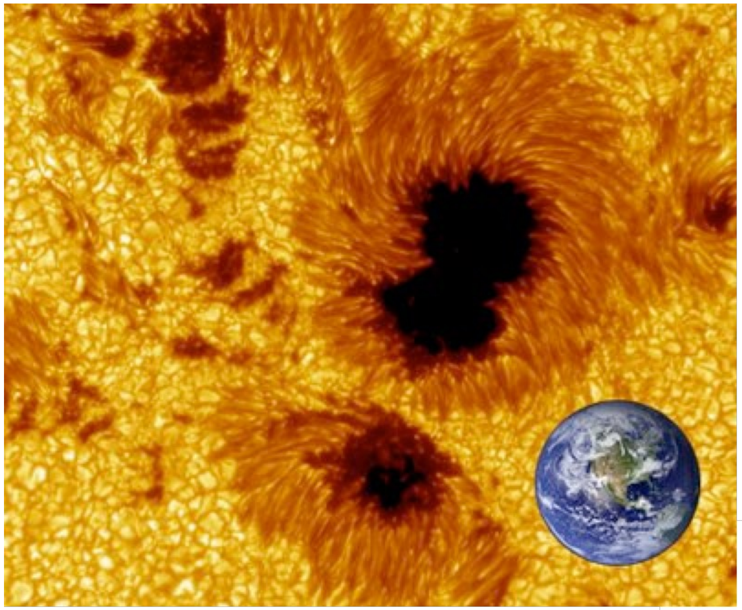


FIGURE 15.17

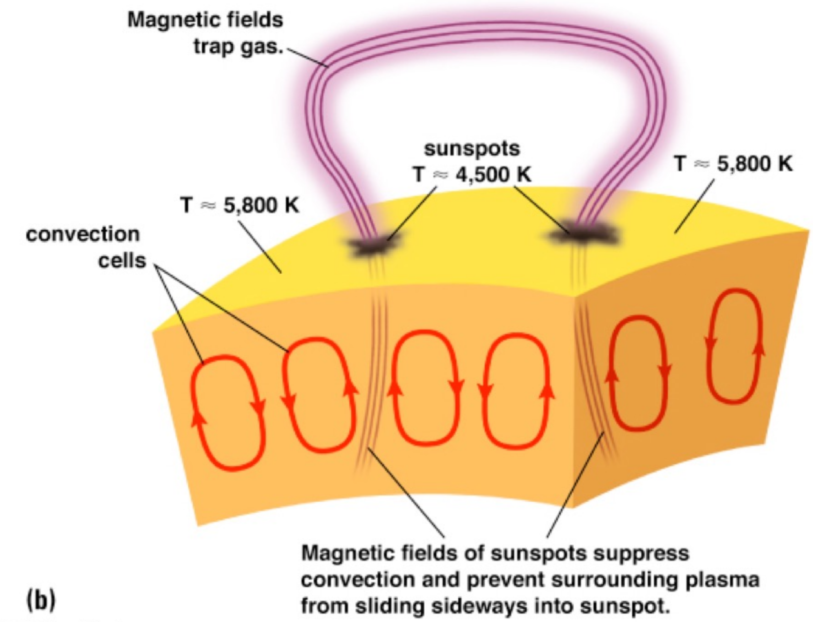


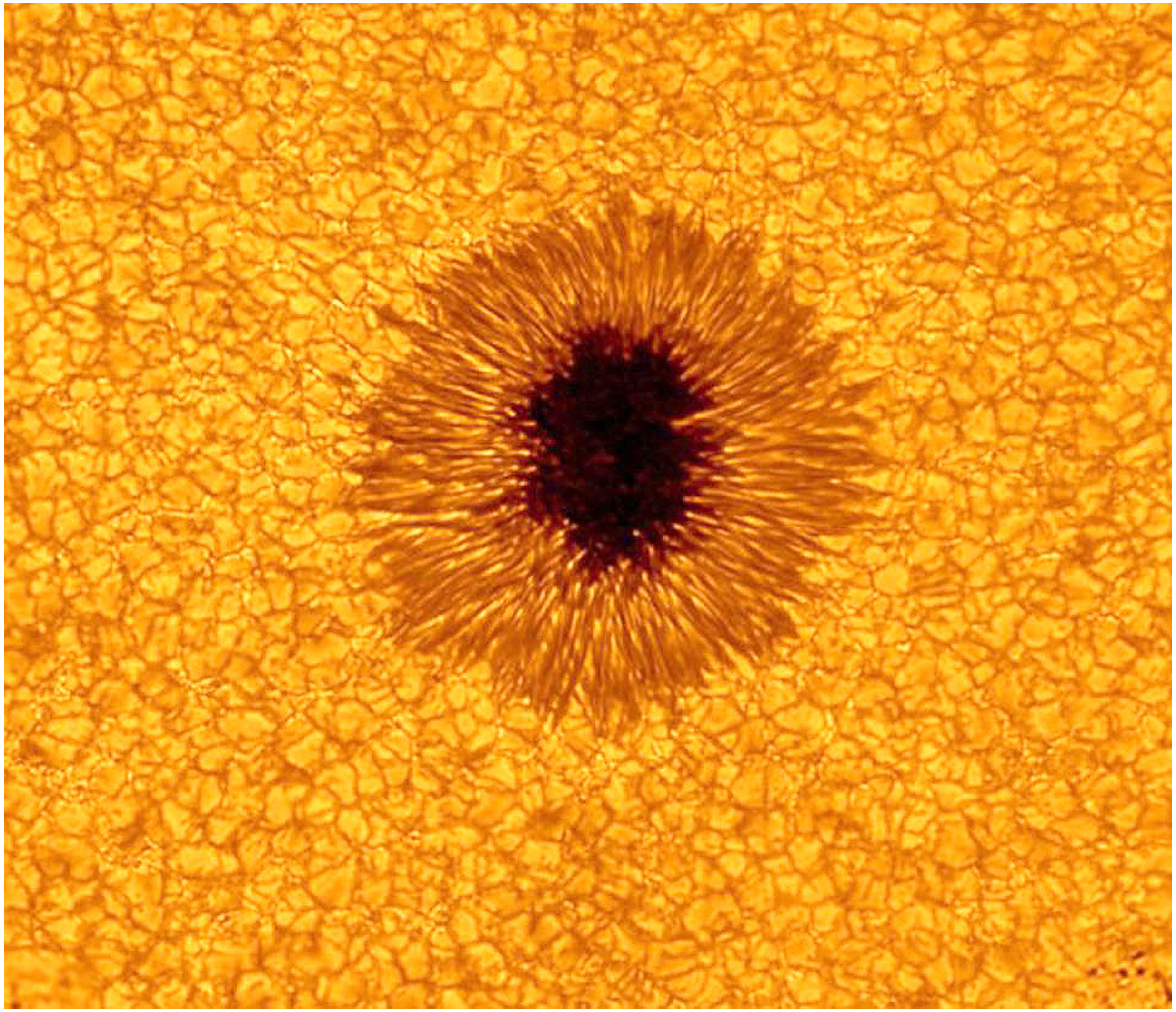
Magnetic Field Lines Wind Up. Because the Sun spins faster at the equator than near the poles, the magnetic fields in the Sun tend to wind up as shown, and after a while make loops. This is an idealized diagram; the real situation is much more complex.

Impact 1: Sunspots



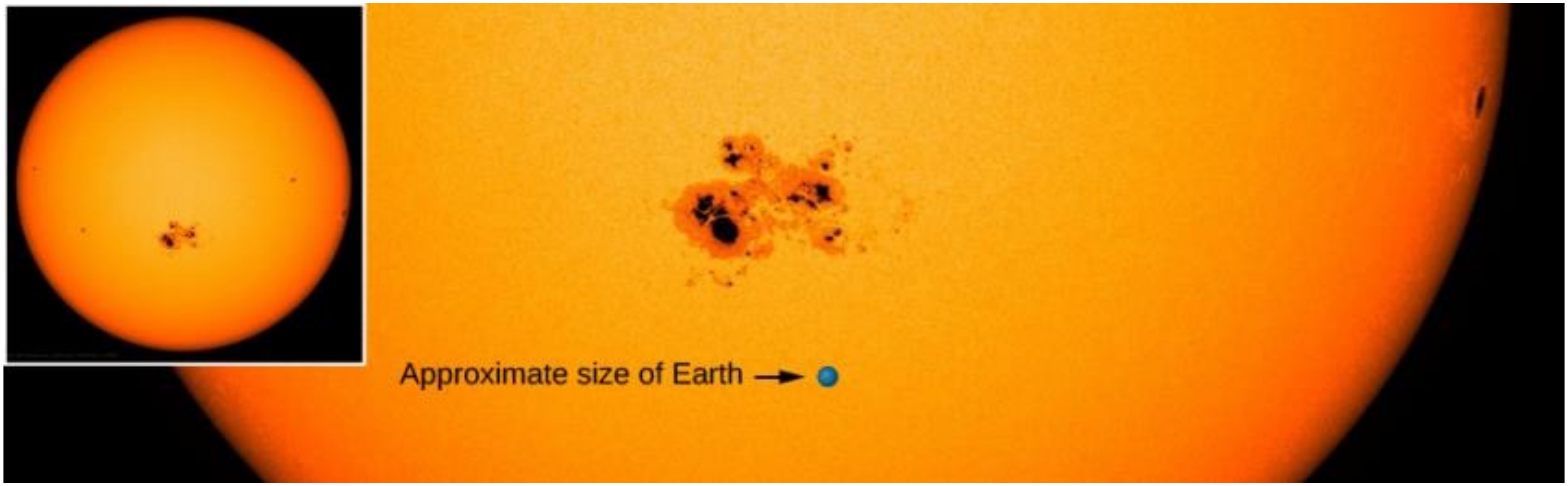
-known since Galileo
- “dark spots” are still bright
    (i.e., the snowflake effect)
-usually occur in pairs
-associated with the “stopage”
    of convection
-2 regions:
    very dark region: umbra
    less dark region: penumbra





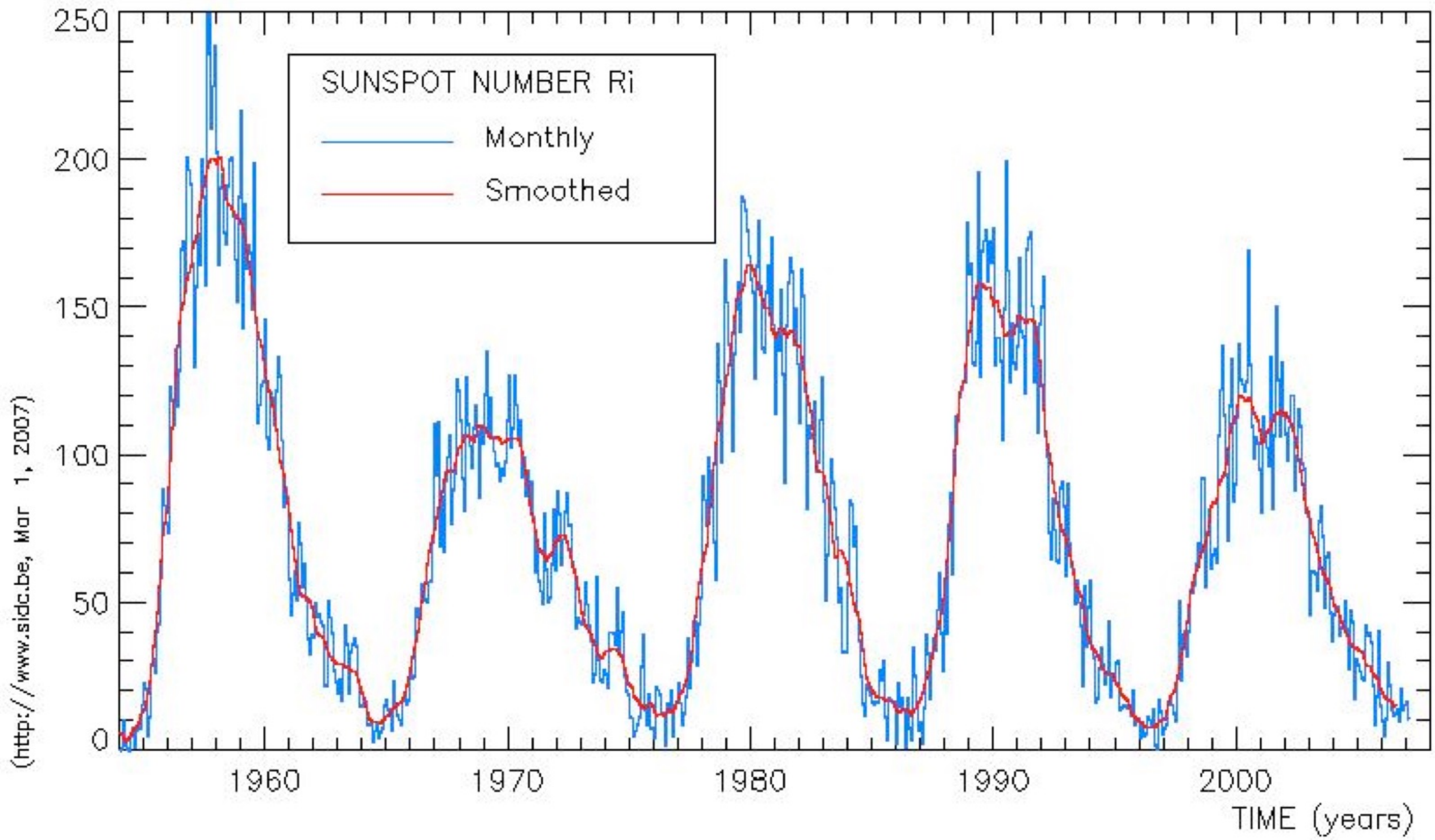
http://www.bbso.njit.edu/

FIGURE 15.5



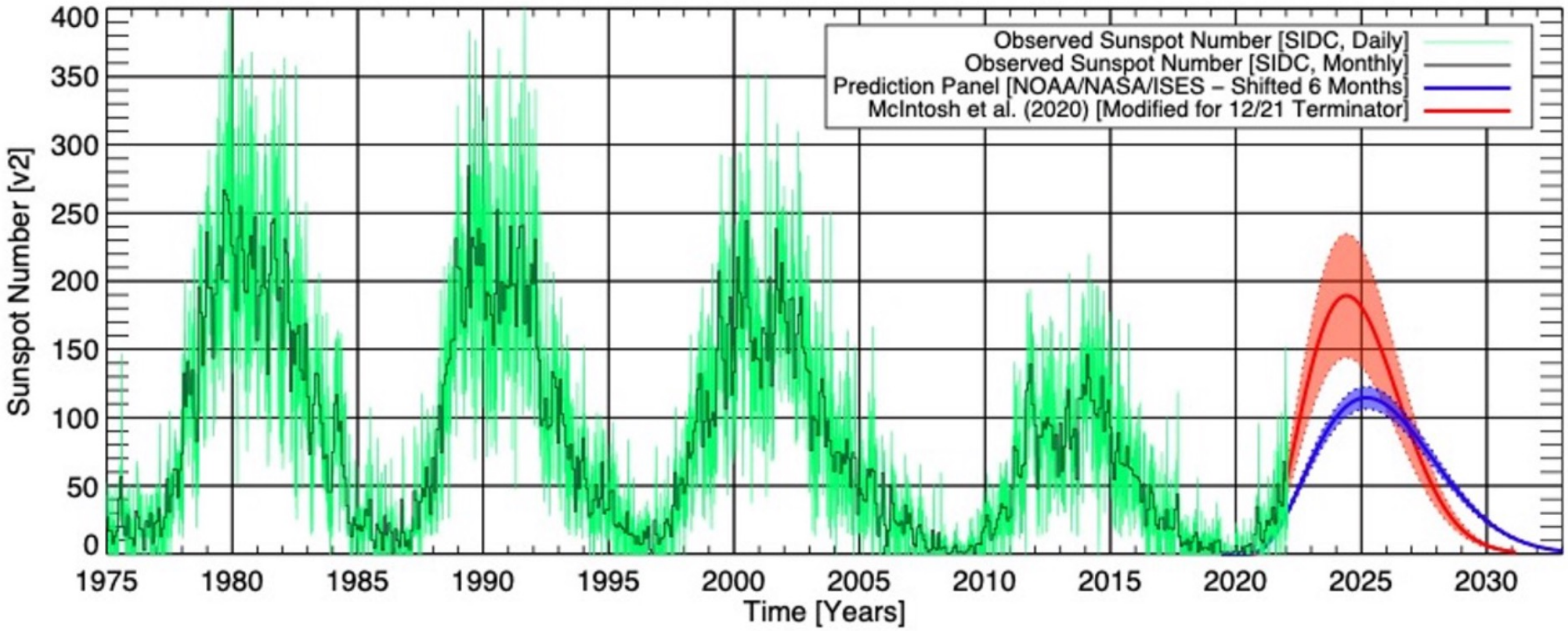
Solar Photosphere plus Sunspots. This photograph shows the photosphere—the visible surface of the Sun. Also shown is an enlarged image of a group of sunspots; the size of Earth is shown for comparison. Sunspots appear darker because they are cooler than their surroundings. The typical temperature at the center of a large sunspot is about 3800 K, whereas the photosphere has a temperature of about 5800 K. (credit: modification of work by NASA/SDO)

Sunspot Cycle

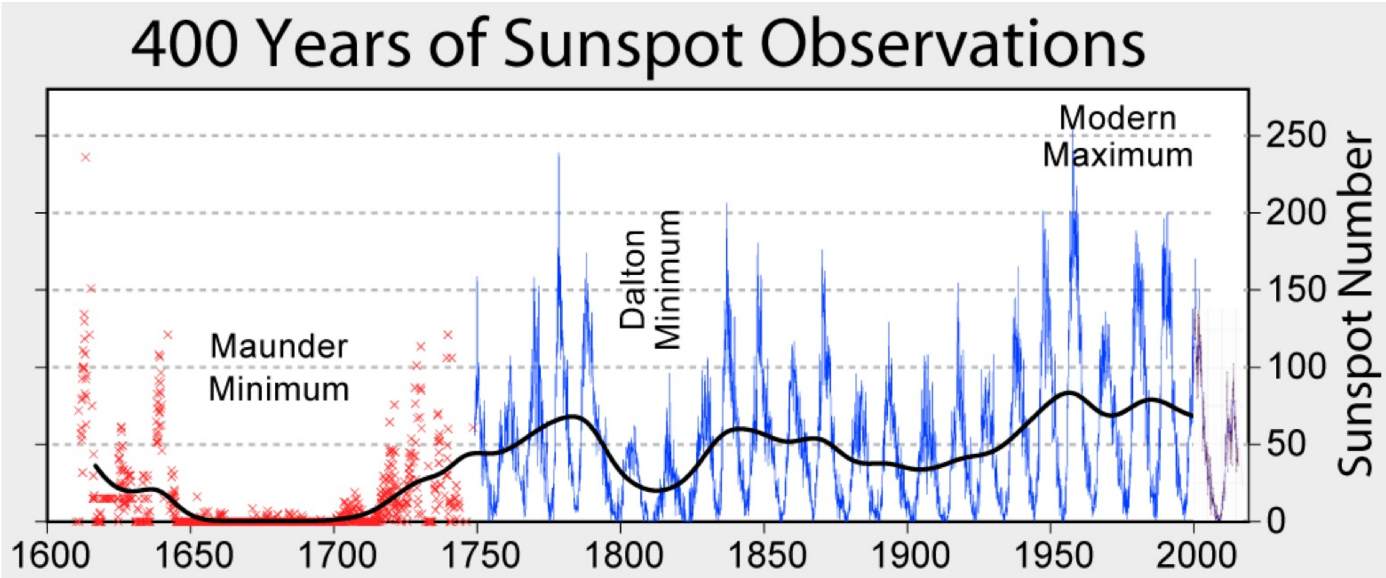


11-year cycle

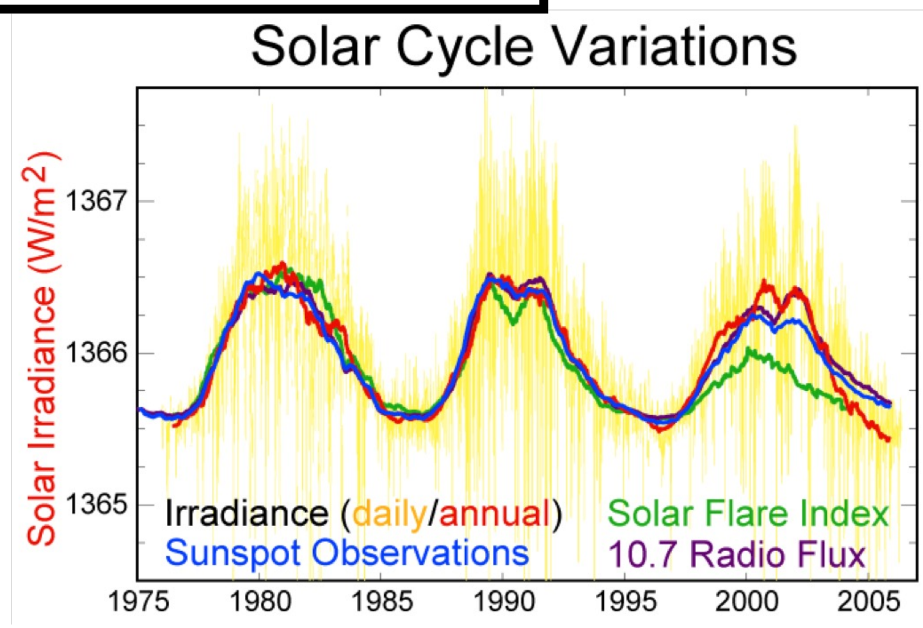
Current Situation?



This chart shows the original predicted number of sunspots, represented as the blue line. The green lines show the observed sunspots, which are trending toward the red line – the McIntosh et al. study – which predicts a higher number of sunspots.



Significance

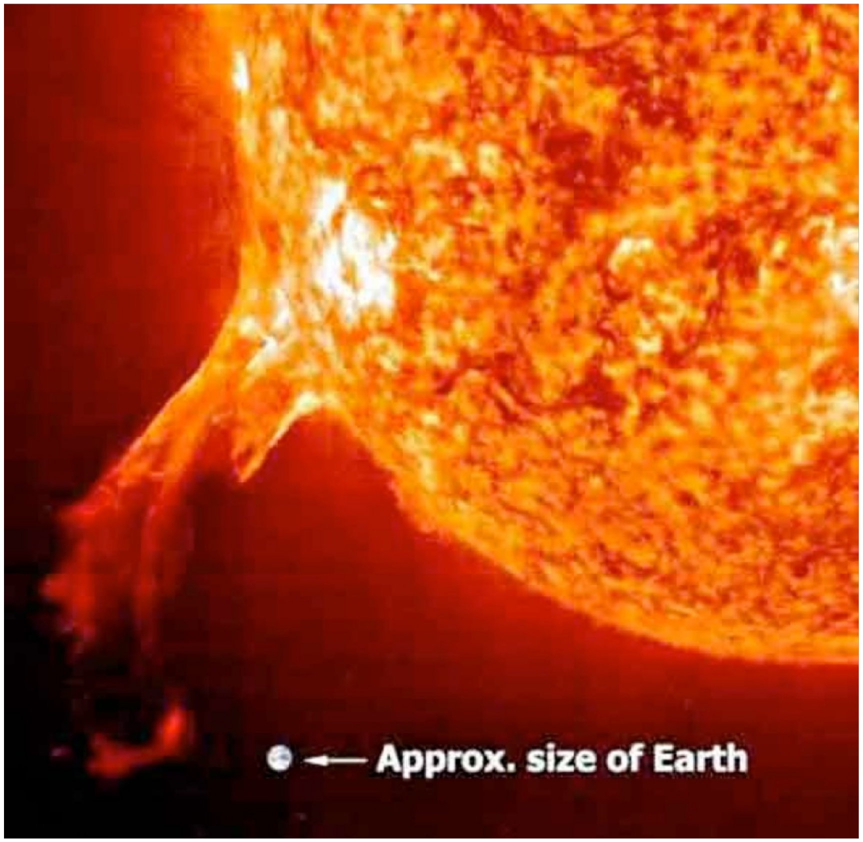


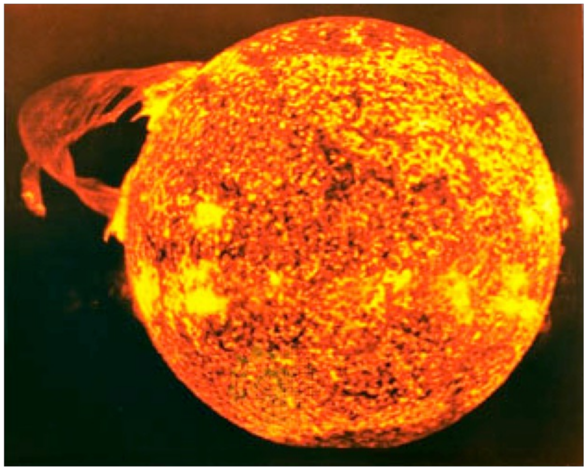
Impact 2: Solar Flares-Coronal Mass Ejections

Sudden brightening observed on the sun's surface associated with massive amounts of energy emission (160,000,000,000 megatons of TNT equivalent)

Usually followed by a Coronal Mass Ejection (CME), BUT THE LINK AND ANY CAUSALITY IS UNCLEAR!

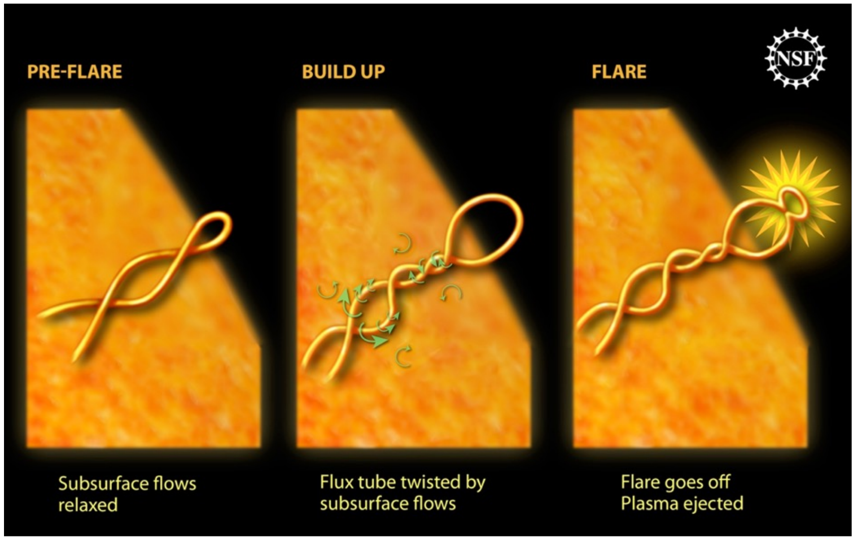
EM waves from flare hit Earth in ~8-min, radiation hits ~2 days after.

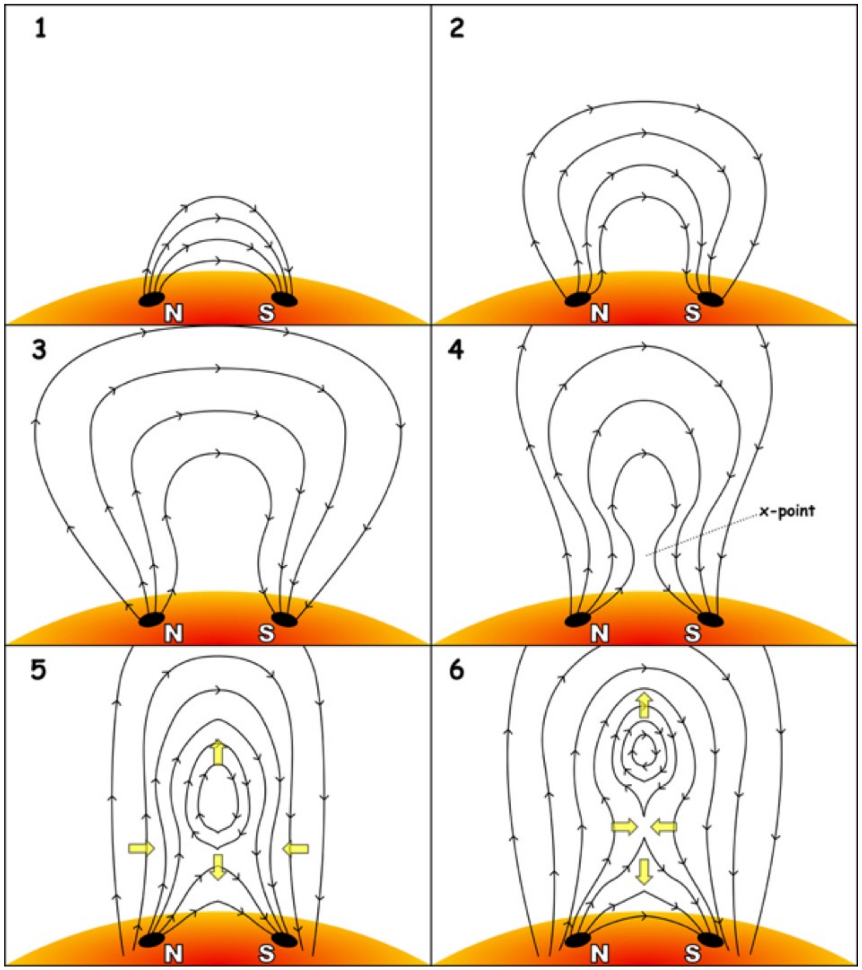


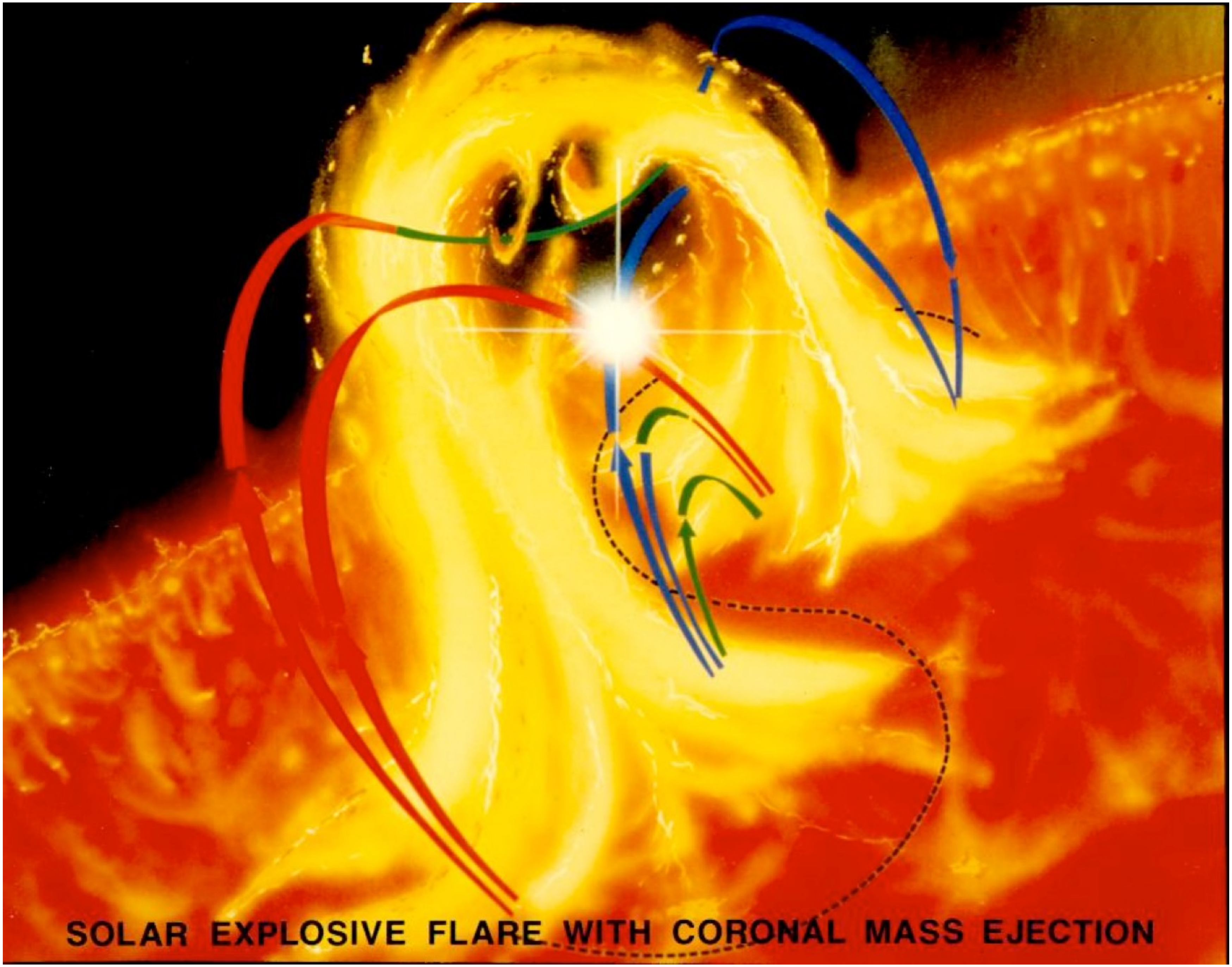


Causes?

Magnetic Reconnection

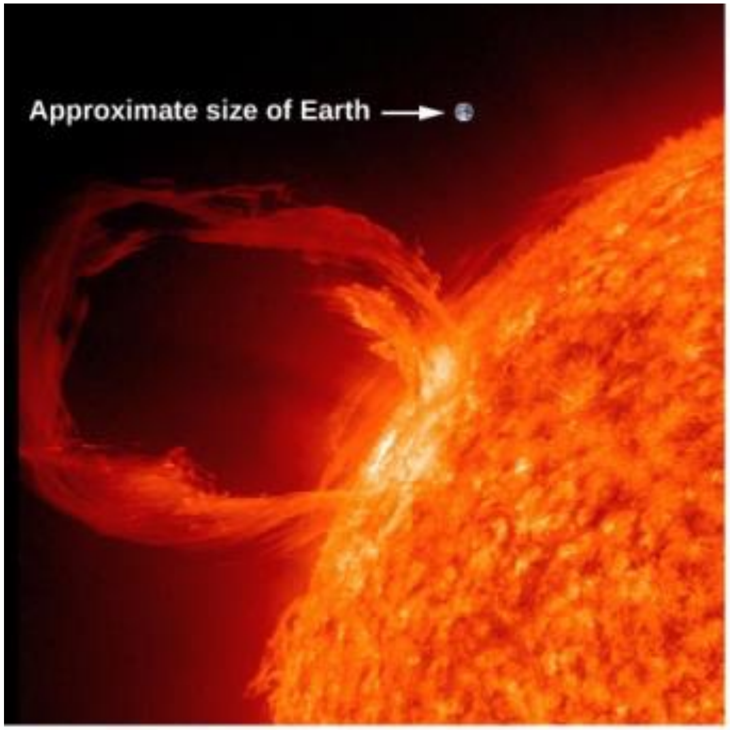




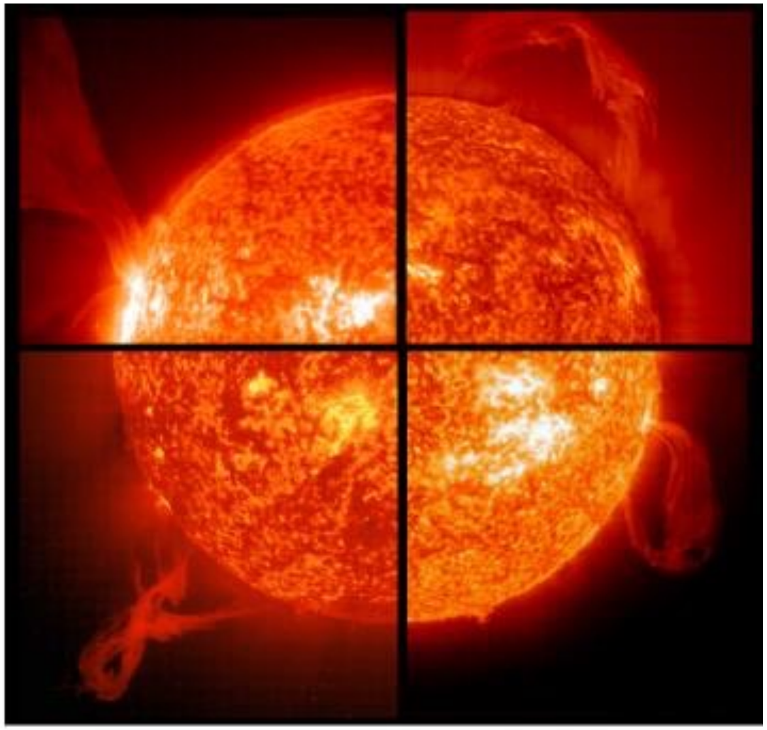


SOLAR EXPLOSIVE FLARE WITH CORONAL MASS EJECTION

FIGURE 15.19



(a)



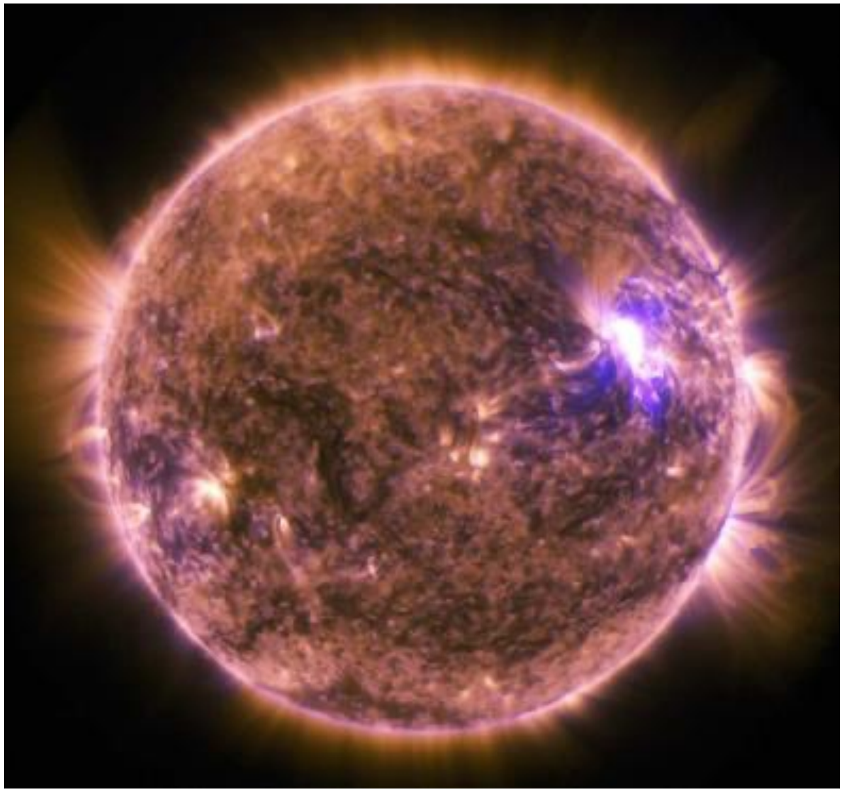
(b)

Prominences.

(a) This image of an eruptive prominence was taken in the light of singly ionized helium in the extreme ultraviolet part of the spectrum. The prominence is a particularly large one. An image of Earth is shown at the same scale for comparison.

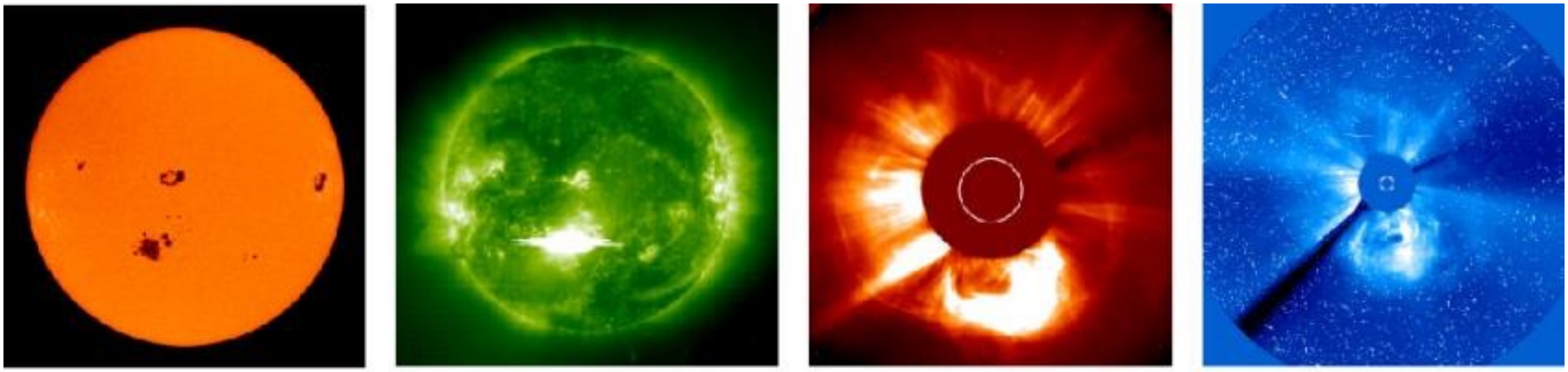
(b) A prominence is a huge cloud of relatively cool (about 60,000 K in this case), fairly dense gas suspended in the much hotter corona. These pictures, taken in ultraviolet, are color coded so that white corresponds to the hottest temperatures and dark red to cooler ones. The four images were taken, moving clockwise from the upper left, on May 15, 2001; March 28, 2000; January 18, 2000; and February 2, 2001. (credit a: modification of work by NASA/SOHO; credit b: modification of work by NASA/SDO)

FIGURE 15.20



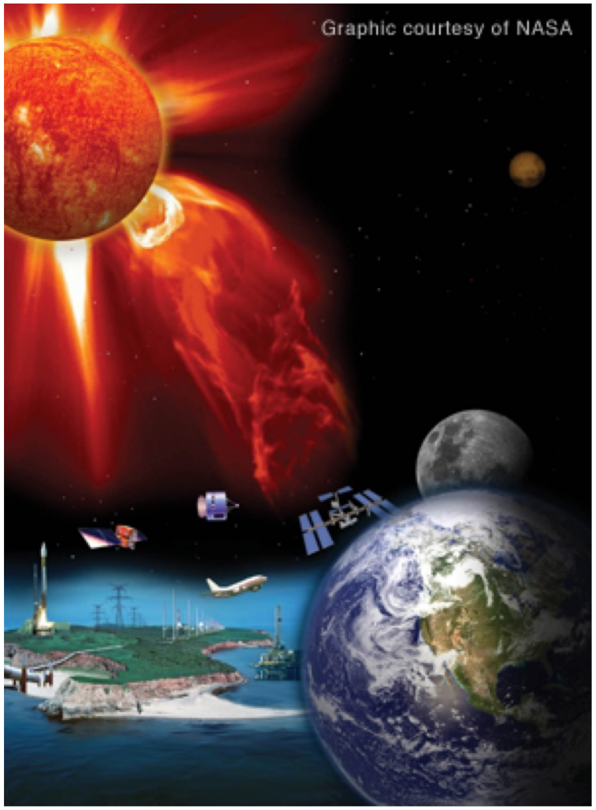
Solar Flare. The bright white area seen on the right side of the Sun in this image from the Solar Dynamics Observer spacecraft is a solar flare that was observed on June 25, 2015. (credit: NASA/SDO)

FIGURE 15.21



(a) (b) (c) (d)

Flare and Coronal Mass Ejection. This sequence of four images shows the evolution over time of a giant eruption on the Sun. (a) The event began at the location of a sunspot group, and (b) a flare is seen in far-ultraviolet light. (c) Fourteen hours later, a CME is seen blasting out into space. (d) Three hours later, this CME has expanded to form a giant cloud of particles escaping from the Sun and is beginning the journey out into the solar system. The white circle in (c) and (d) shows the diameter of the solar photosphere. The larger dark area shows where light from the Sun has been blocked out by a specially designed instrument to make it possible to see the faint emission from the corona. (credit a, b, c, d: modification of work by SOHO/EIT, SOHO/LASCO, SOHO/MDI (ESA & NASA))



Generator of Space Weather