# Chapter 2

# The Structure of the Sun

Astrophysicists classify the Sun as a star of average size, temperature, and brightness—a typical dwarf star just past middle age. It has a power output of about $10^{26}$ watts and is expected to continue producing energy at that rate for another 5 billion years. The Sun is said to have a diameter of 1.4 million kilometers, about 109 times the diameter of Earth, but this is a slightly misleading statement because the Sun has no true “surface.” There is nothing hard, or definite, about the solar disk that we see; in fact, the matter that makes up the apparent surface is so rarified that we would consider it to be a vacuum here on Earth. It is more accurate to think of the Sun’s boundary as extending far out into the solar system, well beyond Earth. In studying the structure of the Sun, solar physicists divide it into four domains: the interior, the surface atmospheres, the ***inner corona***, and the ***outer corona***.

## Section 1.—The Interior

The Sun’s interior domain includes the ***core***, the ***radiative layer***, and the ***convective layer*** (Figure 2–1). The core is the source of the Sun’s energy, the site of thermonuclear fusion. At a temperature of about 15,000,000 K, matter is in the state known as a ***plasma***: atomic nuclei (principally protons) and electrons moving at very high speeds. Under these conditions two protons can collide, overcome their electrical repulsion, and become cemented together by the strong nuclear force. This process is known as nuclear fusion, and it results in the formation of heavier elements as well as the release of energy in the form of ***gamma ray photons***. The energy output of the Sun’s core is so large that it would shine about $10^{13}$ times brighter than the solar surface if we could “see” it.

The immense energy produced in the core is bound by the surrounding radiative layer. This layer has an insulating effect that helps maintain the high temperature of the core. The gamma photons produced by fusion in the core are absorbed and re-emitted repeatedly by nuclei in the radiative layer, with the re-emitted photons having successively lower energies and longer wavelengths. By the time the photons leave the Sun, their wavelengths are mostly in the visible range. The energy produced in the core can take as long as 50 million years to work its way through the radiative layer of the Sun! If the processes in the core of the Sun suddenly stopped, the surface would continue to shine for millions of years.

Above the radiative layer is the convective layer where the temperature is lower, and radiation is less significant. Energy is transported outward mostly by ***convection***. Hot regions at the bottom of this layer become buoyant and rise. At the same time, cooler material from above descends, and giant convective cells are formed. This convection is widespread throughout the Sun, except in the core and radiative layer where the temperature is too high. The tops of convective cells can be seen on the ***photosphere*** as granules. Convective circulation of plasma (charged particles) generates large magnetic fields that play an important role in producing sunspots and flares.

## Section 2.—Thermonuclear Fusion

The nuclear fusion, now occurring in the core of the Sun, turns hydrogen nuclei into helium nuclei. In fact, that is how the elements heavier than hydrogen are made; the thermonuclear fusion at the core of stars can produce the first 26 elements, up to iron. The Sun, because of its relatively small mass, will go through only the first two stages of fusion, the hydrogen-helium stage and the helium-carbon stage.

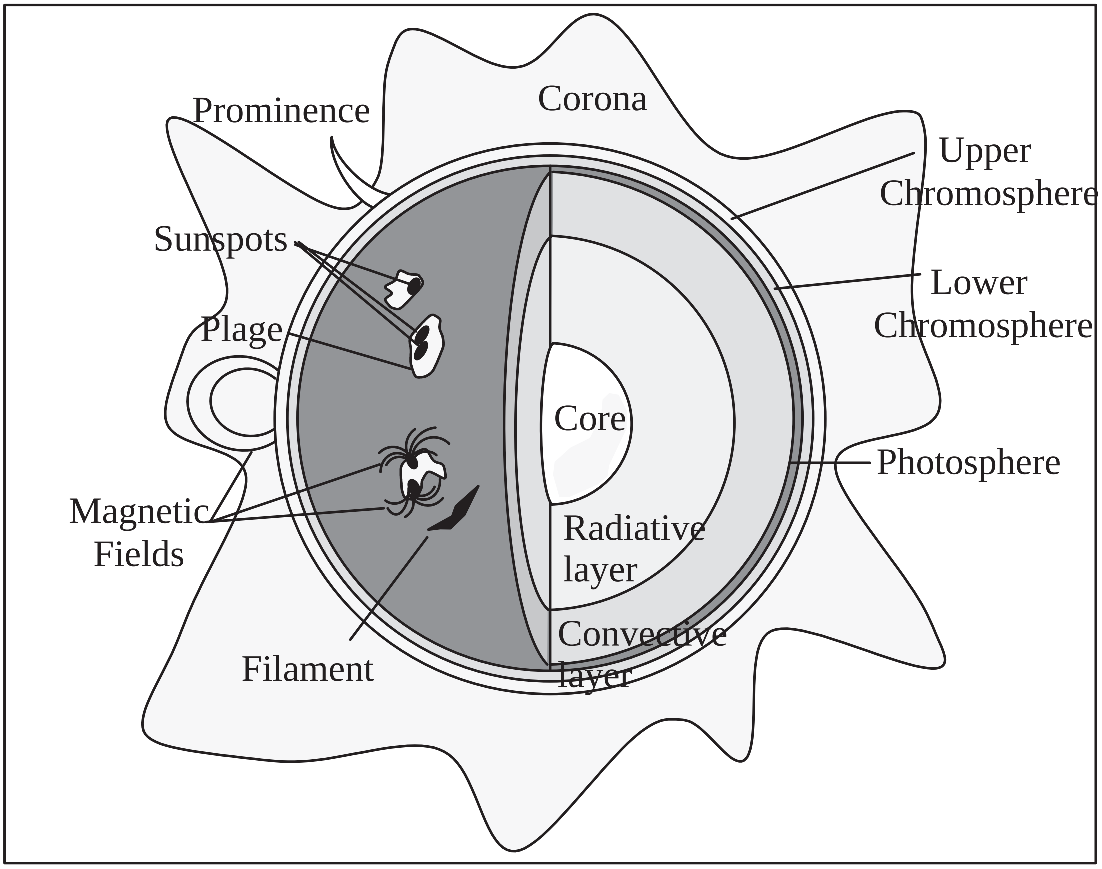


***Figure 2–1.—****The structure of the Sun*

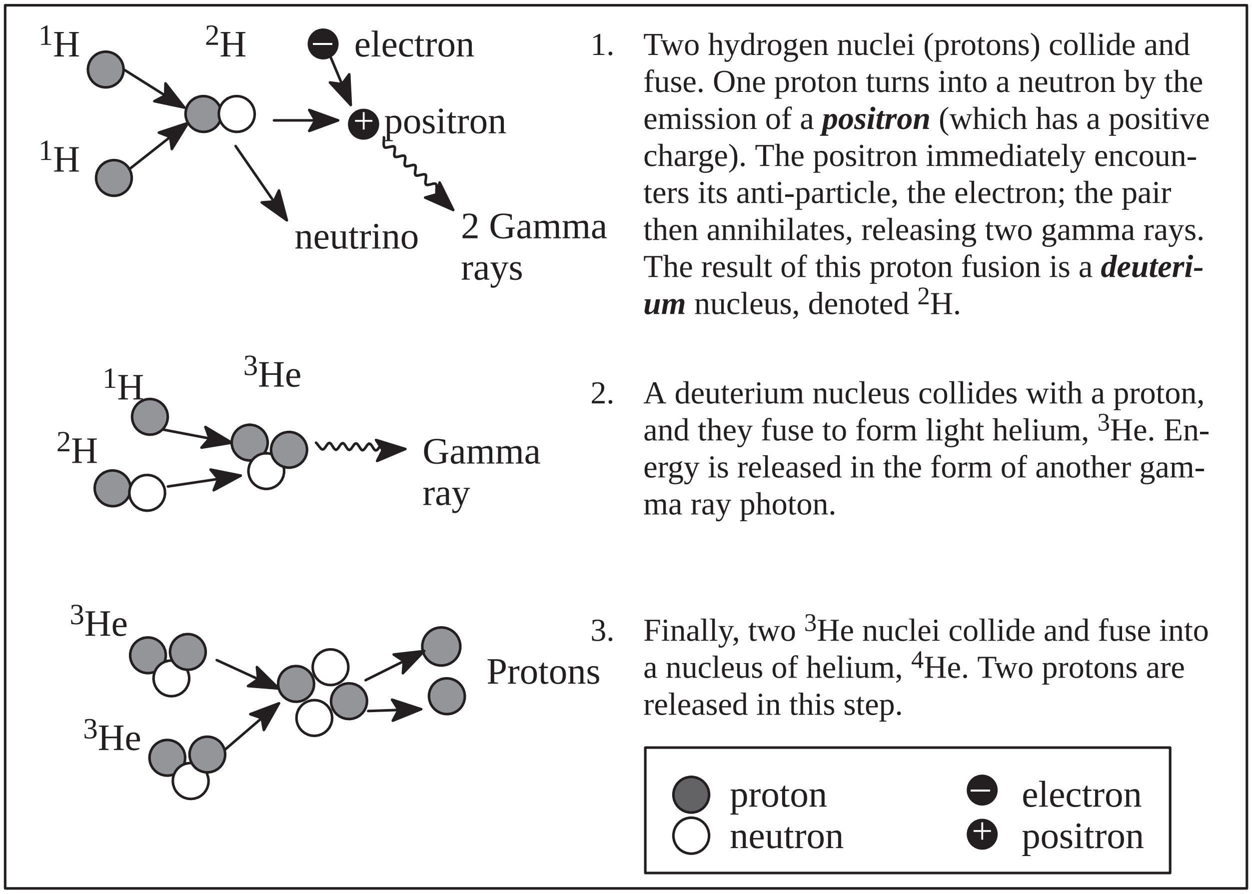
Hydrogen-helium fusion can occur in more than one way, but in any case the temperature must be in the vicinity of 15 million K so that two positively charged particles will be moving fast enough to overcome their electrical repulsion when they collide. The density must be large, and the immense solar gravity compresses the gas so that it is ten times as dense as gold at the center of the Sun. If the two particles can get close enough together, the very short-range strong nuclear force will take effect and fuse them together. The most common fusion reaction in the Sun is shown in Figure 2–2.

If we compare the total mass that went into this three-step fusion reaction to the total mass at the end, we will see that a small amount of mass has disappeared. For this reaction, 0.7 percent of the mass disappears and is converted into energy according to $E = mc^2$ (where E = energy, m = mass and c = the speed of light). The actual energy produced from this reaction (for a given 4 Hydrogen atoms) can be found by

$$E = (0.007)(\text{mass of } 4H)c^2 \; .$$

In order to produce the known energy output of the Sun, 700 million tons of hydrogen are fused into 695 million tons of helium each second! It may be shocking to think that the Sun is losing mass at the rate of 5 million tons per second, but its total mass is so great that this rate of loss can continue for a long time (see Problem #6 at the end of the chapter).

Scientists have dreamed of being able to harness fusion energy to produce electricity on Earth. In attempting the fusion process we are trying to duplicate the conditions in the interior of a star. There are significant problems associated with handling a plasma at 10 to 15 million degrees. The only "container" that can hold material at such high temperatures is a magnetic container. At present, fusion experiments involve the confinement of a plasma in very large toroidal



1. Two hydrogen nuclei (protons) collide and fuse. One proton turns into a neutron by the emission of a ***positron*** (which has a positive charge). The positron immediately encounters its anti-particle, the electron; the pair then annihilates, releasing two gamma rays. The result of this proton fusion is a ***deuterium*** nucleus, denoted $^2$H.

2. A deuterium nucleus collides with a proton, and they fuse to form light helium, $^3$He. Energy is released in the form of another gamma ray photon.

3. Finally, two $^3$He nuclei collide and fuse into a nucleus of helium, $^4$He. Two protons are released in this step.

***Figure 2–2.***—*The proton-proton fusion reaction which occurs in the core of the sun at a temperature of about 15,000,000 K. In this reaction 0.7% of the total mass disappears and is released as energy.*

(donut-shaped) magnetic fields produced by devices called ***tokamaks***. These devices have produced small scale fusion, but the energy input still far outweighs the energy output. The most promising fusion reactions are the ***deuterium-deuterium reaction*** (D-D) and ***deuterium-tritium reaction*** (D-T). Unlike the fusion process in the Sun, we do not attempt the first step in which two protons fuse to form deuterium. This collision has a very low cross-section, meaning that it is very unlikely. The deuterium fuel for Earth-based fusion is extracted from water, which contains a small percent of deuterium and tritium. The D-T reaction has a higher cross-section, making it easier to achieve, but it produces extra neutrons, which makes it more dangerous.

It should be understood that we have achieved uncontrolled fusion here on Earth in the form of the ***hydrogen bomb***. Early nuclear weapons, like those used at Hiroshima and Nagasaki in 1945, were nuclear fission devices which used $^{235}$U as an energy source. Today these fission bombs, sometimes incorrectly called ***atomic bombs***, are used to trigger the larger fusion reaction which turns hydrogen into helium and produces a large amount of energy in one short burst. At the site of such a detonation, the conditions resemble the core of a star with temperatures reaching about 15 million degrees.

## Section 3.—The Surface Atmospheres

The solar surface atmospheres are composed of the photosphere and the chromosphere. The ***photosphere*** is the part of the Sun that we see with our eyes—it produces most of the visible (white) light. Bubbles of hotter material well up from within the Sun, dividing the surface of the photosphere into bright granules that expand and fade in several minutes, only to be replaced by the next upwelling. The photosphere is one of the coolest layers of the Sun; its temperature is about 6,000 K (Figure 2–4).

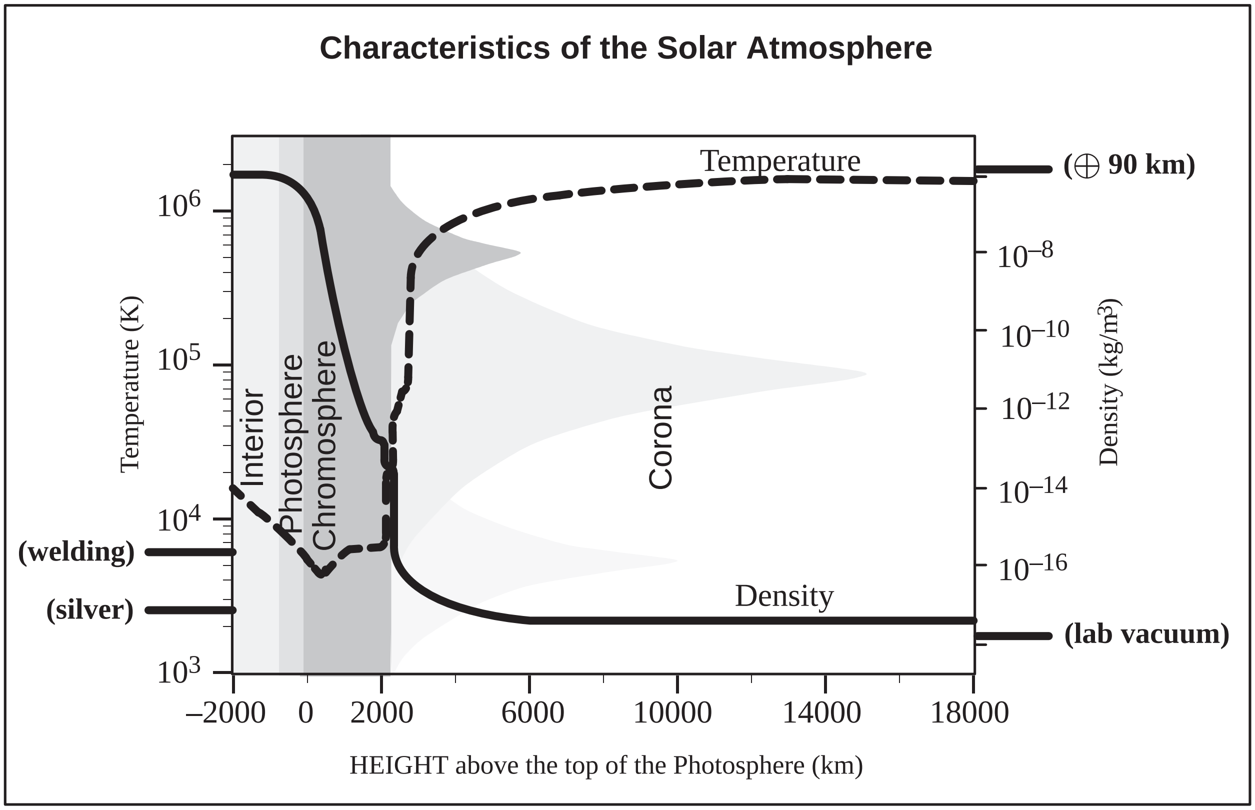


***Figure 2–4.****—Temperature (dashed line) and density (solid line) of the of the Solar Atmosphere. Note that the highest density on the scale here is still only as dense as the Earth's atmosphere at 90 km up. The melting temperature of silver is near the bottom of the temperature scale shown here. (after* A New Sun: The Solar Results from Skylab, *John A. Eddy, NASA, 1979, p. 2.)*

Sometimes huge magnetic-field bundles break through the photosphere, disturbing this boiling layer with a set of conditions known collectively as ***solar activity***. These magnetic fields create cooler, darker regions, which we see as ***sunspots***. The appearance and disappearance of sunspots in an 11-year cycle is discussed in more detail in Chapter 3, section 2. Early observers of sunspots quickly noted that they appear to migrate across the disk of the Sun as it rotates.*

The Sun's rotation rate differs according to latitude: as seen from the Earth, the equatorial region rotates with a period of about 27 days, while the rotational period closer to the poles is about 32 days (Table 2–1).

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* The Sun's rotational period as observed from Earth is known as the ***synodic period***. Because the Earth moves about $^1/_{12}$ of the way around the Sun while the Sun makes one rotation, the synodic period is somewhat greater than the period that would be observed from the ***fixed stars***, known as the ***sidereal period***.

## Table 2–1. — The Sun’s Vital Statistics

modified from *A New Sun: The Solar Results from Skylab*, John A. Eddy, NASA, 1979, p. 37.

| | |
|---|---|
| Age | At least 4.5 billion years in present state |
| Chemical composition of photosphere ( by mass, in percent): | |
| Hydrogen | 73.46 |
| Helium | 24.85 |
| Oxygen | 0.77 |
| Carbon | 0.29 |
| Iron | 0.16 |
| Neon | 0.12 |
| Nitrogen | 0.09 |
| Silicon | 0.07 |
| Magnesium | 0.05 |
| Sulfur | 0.04 |
| Other | 0.10 |
| Density (water=1000): | |
| Mean density of entire Sun | 1410 $kg/m^3$ |
| Interior (center of Sun) | 160000 $kg/m^3$ |
| Surface (photosphere) | $10^{-6}$ $kg/m^3$ |
| Chromosphere | $10^{-9}$ $kg/m^3$ |
| Low corona | $10^{-13}$ $kg/m^3$ |
| Sea level atmosphere of Earth (for comparison) | 1.2 $kg/m^3$ |
| Diameter (measured at the Photosphere) | $1.39x10^6$ km (or 109 times the diameter of Earth and 9.75 times the diameter of Jupiter, the largest planet |
| Distance | |
| mean distance from Earth | $1.5x10^8$ km |
| Variation in distance through the year | ±1.5 percent |
| Magnetic field strengths for typical features: | |
| Sunspots | 0.3 tesla |
| Polar field | $10^{-4}$ tesla |
| Bright, chromospheric network | 0.0025 tesla |
| Ephemeris (unipolar) active regions | 0.0020 tesla |
| Chromospheric plages | 0.02 tesla |
| Prominences | $10^{-3}$ to $10^{-2}$ tesla |
| Earth (for comparison) | $7 \times 10^{-5}$ tesla at pole |
| Mass | $1.99x10^{30}$ kg (or 333 000 times the mass of Earth) |
| Rotation (as seen from Earth): | |
| Of solar equator | 26.8 days |
| At solar latitude 30° | 28.2 days |
| At solar latitude 60° | 30.8 days |
| At solar latitude 75° | 31.8 days |
| Solar radiation: | |
| Entire Sun | $3.83x10^{23}$ kW |
| Unit area of surface of Sun | $6.29x10^4$ $kW/m^2$ |
| Received at top of Earth’s atmosphere | 1370 $W/m^2$ |
| Surface brightness of the Sun (photosphere): | |
| Compared to full Moon | 398 000 times |
| Compared to inner corona | 300 000 times |
| Compared to outer corona | $10^{10}$ times |
| Compared to daytime sky on Pikes Peak | 100 000 times |
| Compared to daytime sky at Orange, N.J. | 1000 times |
| Temperature: | |
| Interior (center) | 15 000 000 K |
| Surface (photosphere) | 6050 K |
| Sunspot umbra (typical) | 4240 K |
| Penumbra (typical) | 5680 K |
| Chromosphere | 4300 to 50 000 K |
| Corona | 800 000 to 3 000 000 K |
| Volume | $1.41x10^{27}$ $m^3$ (or 1.3 million times the volume of Earth) |

These periods can easily be determined by watching sunspots over several days (Figure 2–5). It is now known, however, that these periods correspond to the photosphere where the sunspots reside, and that the rotational period varies in the different layers above the photosphere. This complicated variation of rotational period according to latitude and depth contributes to the shearing and twisting that give rise to solar activity.

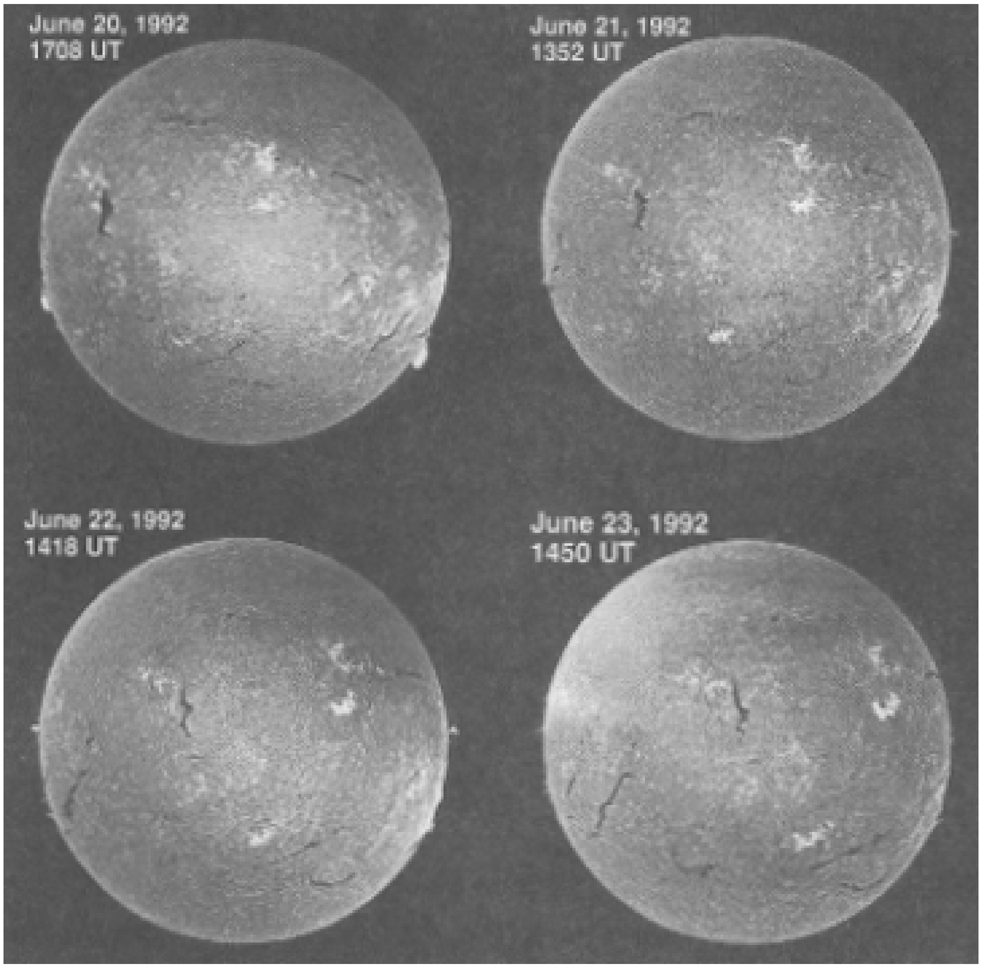

***Figure 2–5.****—Photos of the Sun on four consecutive days taken in Hα light. Features can be seen to move as the Sun rotates.*

The chromosphere lies just above the photosphere, and is slightly cooler at its base. It is called ***chromo*** because of its color, which can only be seen when the much brighter light from the photosphere is eliminated. When a ***solar eclipse*** occurs, the red chromosphere is seen briefly just before and after the period of total eclipse. When viewed in white light, the chromosphere is transparent to the brilliant light emitted underneath it by the photosphere. But when viewed only in the red light produced by hydrogen (called Hα), the chromosphere is seen to be alive with many distinctive features, including long dark filaments and bright areas known as ***plage*** that surround sunspot regions.

The chromosphere is also characterized by cellular convection patterns, but these cells are much larger than the granules of the photosphere. Near the boundaries of these cells are concentrated magnetic fields that produce vertical jets of material called ***spicules***. Although spicules are considered to be small features of the quiet sun, they are actually about the size of Earth! ***Flares*** are much larger and more explosive. The active regions associated with sunspots produce strong magnetic fields, which arch up through the chromosphere and become conduits for material when explosive flares erupt. The cause and timing of these eruptions are of great interest to scientists but are not well understood.

Solar activity is very apparent in the chromosphere, and has a wide range of time scales. Flares begin in seconds and end after minutes or hours. Active regions last many weeks, and may flare many times before fading away. The number of sunspots and active regions rises and falls in a mysterious 11-year cycle. Behind all of these phenomena and time scales are the Sun's magnetic fields, deriving their energy from the interplay of the Sun's rotational and convective motions. The magnetic fields are always changing, yet there is a 22-year magnetic cycle that seems to underlie all of the Sun's activity. The activity that we can observe on the photosphere and chromosphere is merely a "symptom" of what is happening inside the Sun. Although we have many clues, the detailed physics of stellar interiors is still largely a mystery.

## Section 4.—The Inner Corona

The inner corona is the wispy halo, extending more than a million kilometers out into space, that can be seen when the brilliant disk of the Sun is blocked by the Moon during a total eclipse (Figure 2–6). The cause of the high temperature of the corona, about 2,000,000 K, is not well understood. The corona is a large source of x-rays which do not penetrate Earth's atmosphere. With instruments on satellites we can look at the corona in x-ray wavelengths and see many details that do not appear in visible light. From this vantage point it is clear that magnetic arches dominate the structure of the corona. Large and small magnetic active regions glow brightly at x-ray wavelengths, while open magnetic field* structures appear as gaping ***coronal holes***. The coronal material is generally confined by closed magnetic field structures, anchored at both ends, but the open field structure of coronal holes allows the corona to escape freely to form fast, low density streams in the ***solar wind***. This material travels outward and causes disturbances in Earth's magnetic field. Because of their effects on Earth, we would like to be able to predict when and where coronal holes will form, but as yet we cannot do this.

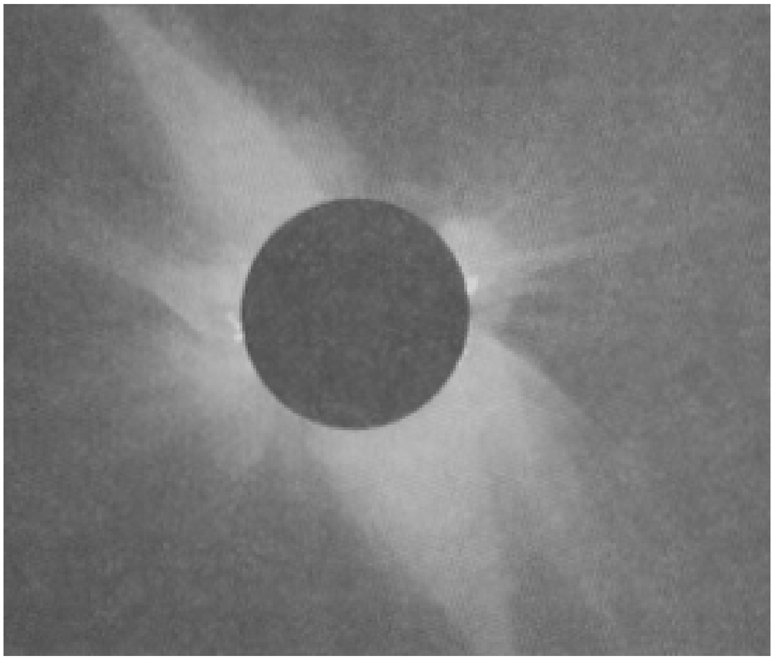

***Figure 2–6.****—Total solar eclipse of July 11, 1991 as seen from Baja California. This digital mosaic is derived from five individual photographs by Dennis DiCicco (Sky and Telescope) and Gary Emerson (E. E. Barnard Observatory); digitized by David Sime, NCAR's High Altitude Observatory; processed by Steve Albers. The image comes close to capturing the visual appearance of the eclipse through high-power binoculars.*

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*The concept of an open field line is one where the magnetic field line extends so far out before returning that in the close proximity of the Earth-Sun system, the line appears "open."

## Section 5.—The Outer Corona

The outer corona extends to Earth and beyond. Its existence is not immediately obvious, since it cannot be seen directly; astrophysicists did not become aware of it until the 1950's. Watching the behavior of comets, Ludwig Biermann realized in the early 1950's that the solar corona must be expanding outward. By 1958, Eugene Parker concluded from theoretical models that particles streaming off the Sun were necessary to maintain the dynamic equilibrium of the corona. Parker's mathematical prediction that particles streamed from the Sun at speeds of several hundred kilometers per second was verified in the early 1960s when satellites detected coronal outflow. This outflow came to be called the solar wind and its speed was accurately measured in 1962 by the Mariner 2 spacecraft bound for Venus. As Parker had predicted, this speed averaged about 400 km/s.

In the 30 years since the discovery of the solar wind, we have learned much more about it, and its effects on Earth. The solar wind streams radially outward from the Sun. Solar rotation swings the source around so that the individual streams describe ***Archimedian spirals*** (Figure 2–7); the solar wind speed and density vary according to the conditions on the Sun. This variation in the solar wind intensity began to make more sense after the discovery of coronal holes during the Skylab missions in the early 1970s. Using an x-ray telescope, the Skylab astronauts took many pictures of the Sun which showed coronal holes as large, dark regions with open magnetic field lines where the corona streams outward. These regions grow and shrink, and move around on the Sun in ways that are not yet understood. When a coronal hole is facing Earth, the solar wind reaching Earth is more intense.

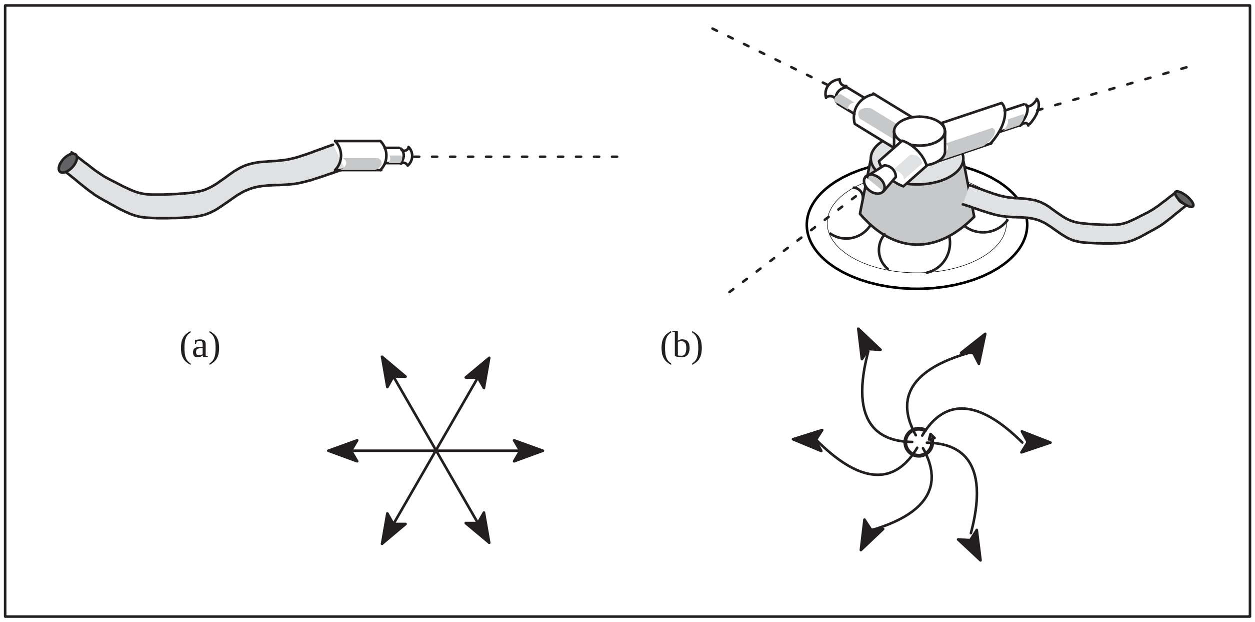

***Figure 2–7.****—(a) The pattern that particles in the solar wind would make if the Sun did not rotate; the outflowing wind is radial. An analogy would be a garden hose. (b) The "Archimedes spiral" pattern produced by solar rotation. An analogy would be a garden sprinkler. During the four days that it takes the solar wind to travel to Earth, the Sun rotates about 60 degrees.*

The nature of the solar wind is also determined by flare and ***prominence*** activity on the Sun. During times of high activity, plasma is hurled off the Sun in vast eruptions that are energized by the turbulent magnetic fields in the inner corona. If ejected mass travels outward and strikes the Earth, we can feel many effects. This is discussed in Chapter 4, section 2.

## Problems and Questions

Refer to the Table of Vital Statistics (2–1) and Figure 2–4 for data to work these problems.

1. Calculate the time required for each of the following to travel the Sun-Earth distance:
   - (a) visible light produced in the photosphere.
   - (b) x-rays from a flare.
   - (c) solar wind particles traveling at 400 km/s.
   - (d) a jet aircraft traveling at 500 mph.
2. At what speed does the eastern limb (at the left as we look at the disk) of the Sun near the equator move toward us?
3. Using Figure 2–4, estimate the temperature of
   - (a) the photosphere,
   - (b) the chromosphere
   - (c) the corona at 18,000 km up. Note that the temperature scale is logarithmic.
4. Repeat #3 for density rather than temperature.
5. Estimate how much energy is produced from one fusion reaction in the core of the Sun. How many reactions would have to occur each second to produce the solar power output of $10^{26}$ watts?
6. Assuming that the present processes within the Sun will continue (not true), estimate how long the Sun can last if it is losing mass at the rate of 5 thousand million kilograms per second?
7. Estimate the speed of protons in the core of the Sun at 15 million K.
8. A typical count of solar wind reaching Earth is about $10^7$ particles per cubic meter.
   - (a) Compare this to the number of particles in the air of this room (hint: remember the ideal gas law).
   - (b) Estimate the particle density of the photosphere which has an average density of about $10^{-6}$ kg/m$^3$.
   - (c) Estimate the particle density of a neutron star.
9. If a certain region of the Sun is observed to have a synodic rotation period of 28 days, what would the sidereal period be? Hint: a picture of the Earth in various positions in its orbit around the Sun might be helpful.