Chapter 8

The Nearest Star, The Sun

8-1. General Facts

1. The Sun is an entirely gaseous, incandescent body that generates energy mainly by thermonuclear processes that occur deep in the center.

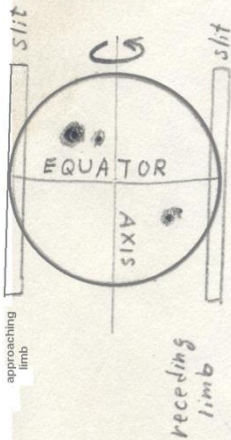2. The solar diameter is about 864,000 mi. or 109 $R_\oplus$

3. The average density of the sun is 1.4 times H_2O, the density being highest near the center and decreasing continuously outwards

4. The surface temperature is about 5800 K = 11,500 °F

5. Mass of Sun = 2.0 × 10^{33} gm.

6. ROTATION : (counterclockwise as seen from NEP)

   a. Measurement

   (1). Observing Sunspots (Galileo 1610)

   (2). Doppler shifts of solar limbs yield speeds of approaching and receding limbs. The spectroscopic results yield slightly lower rates than the sunspot observations because the solar Fraunhoffer lines originate at a higher level in the solar atmosphere than the location of the sunspots.

   b. Results: Rotation different at different latitudes, hence the sun can not be solid.

ϕ	Doppler	Sunspots
0°	24^d.6	25.1
30°	26^d.4	26.5
75°	33^d.0	33.0

   c. Axis of rotation is tilted 7° from the ecliptic plane. Hence sunspots move in curved paths as seen from Earth.

8-2. Structure

8-2.1 The photosphere

The visible surface of the Sun is called the photosphere.   See the schematic below:

SOLAR STRUCTURE

Prominence

CHROMOSPHERE
var. temp.

Spicules

Granulation

Radiative Zone

Sunspot pair
4500° K

PHOTOSPHERE

core

magnetic field

5800 K
$\rho = 10^{-5}$ atmos.

6 × 10³ K

Flare

CORE: $T \simeq 12 \times 10^6$ K

$4 H \rightarrow 2 He + \gamma$

CORONA
$T \simeq 2 \times 10^6$ K
$\rho = 10^{-12}$ atoms.

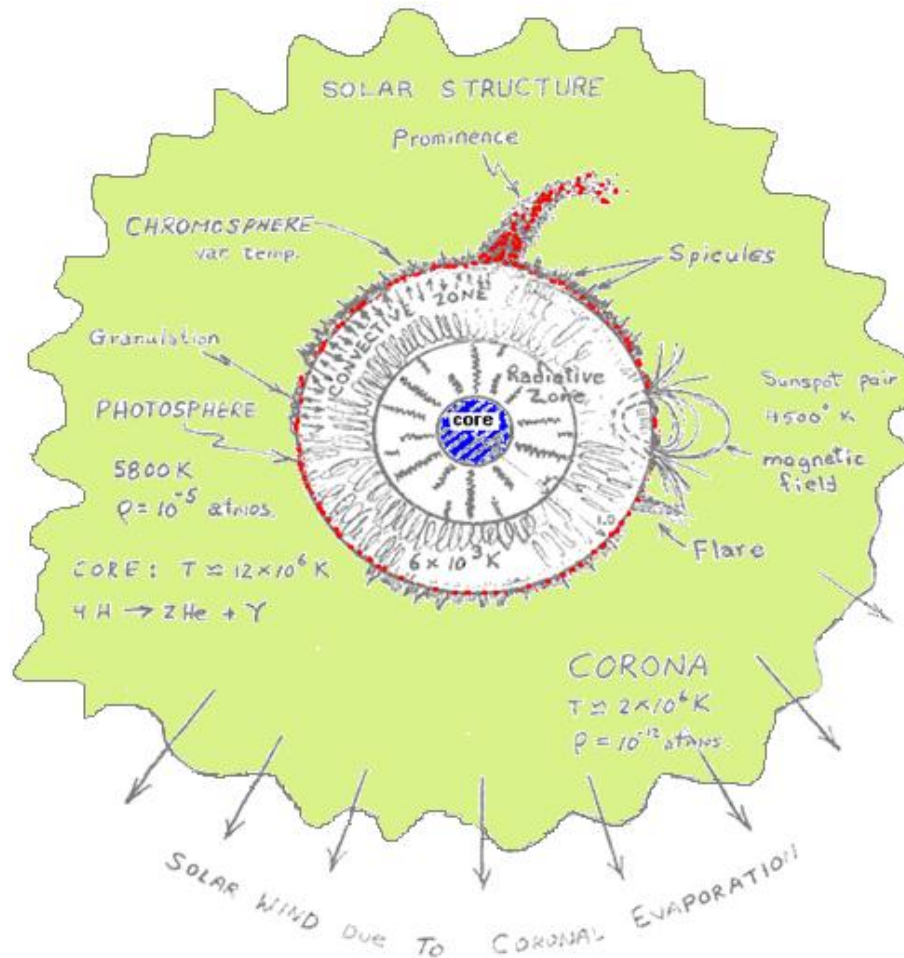SOLAR WIND DUE TO CORONAL EVAPORATION

Figure 1. A schematic diagram showing the cross-sectional structure of the Sun along with some observational solar phenomena and data.

The photosphere is not a real surface, since the Sun is entirely gaseous. Rather, the photosphere is a layer in the Sun beneath which very little radiation escapes into space. The optical depth into the Sun at this layer is said to be 1.0. The optical depth, τ, is a number such that the attenuation of any radiation attempting to penetrate the upper layers of the Sun is given by:

$$I = I_o\, e^{\tau} \qquad\qquad (8\text{-}1.1)$$

In this equation, I_o is the intensity of the radiation at the bottom of the layer and I is the surviving intensity that escapes from the Sun. Also see equation (10-4) in Z&G, who use flux rather than intensity. One should see that if $\tau = 0.0$, there is no attenuation and $I = I_o$. That is, the layer is completely transparent. When $\tau = 1$, $I = 0.368 I_o$, that is, slightly more than one third of the radiation incident at the bottom of the layer penetrates through the upper layers to leave the Sun. So when one observes the Sun, one is actually seeing radiation coming from different layers of different temperatures, but the radiation coming from the deeper layers is relatively weak compared to the radiation emanating from the higher layers. This is true for all stars and this also applies to the atmospheres of planets.

   The photosphere has noticeable limb darkening. That is, the Sun is distinctively dimmer near the edges. This is because radiation observed coming from the limbs or edges of the Sun originate in higher, cooler layers. This is because the radiation from the deeper hotter layers must travel along a longer path to reach the observer and hence there is more

absorption. This is the same phenomenon that happens when either the Moon or Sun are seen low in the sky. They appear dimmer because the path length of the radiation through the Earth's atmosphere is longer. See Figure 2.

Through a telescope, the visible surface of the Sun displays the following features:

1. Granulation. That is, the surface of the Sun appears mottled or granular. The granules are the tops of convection cells that extend down below the photosphere into the convective zone. They have an average diameter of about 700 km. There appears to be some ambiguity about this number in Z&G.

2. Sunspots, which were first discovered by Galileo in 1610. These are cooler patches of the Sun's photosphere with a temperature of about 4500K. Sunspots are composed of two parts:

    a. The umbra which is the central cooler area and

    b. The penumbra which is a warmer fringe of complex structure surrounding the umbra.

Sunspots usually occur in pairs with each member of the pair connected by magnetic field lines. Sunspots usually occur between latitudes 5 and 30 degrees and are rarely seen above 35 degrees. The spots range in size from very small to monsters 80×10^3 km in size that could easily swallow the Earth.

Sunspots wax and wane in approximately and 1.11 year cycle that was discovered in 1851. Each new cycle begins when spots first appear at the higher latitudes. As the cycle proceeds, spots appear to be more numerous and begin to form at lower latitudes. The cycle ends as spots begin to diminish at about latitude $5°$.

3. Faculae. These are bright areas associated with sunspots and are hotter areas of the photosphere. Though the sunspots are cooler areas of the photosphere, the associated hotter faculae more than compensate for the radiation lost coming from the spots. Therefore, the Sun is actually brighter when there are sunspots.
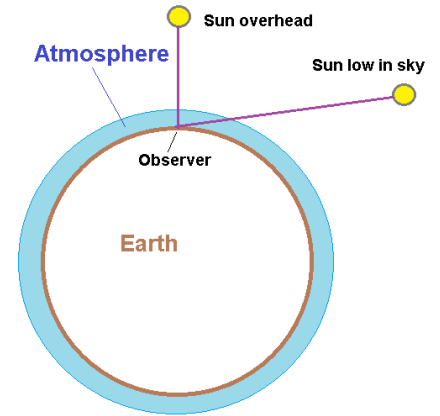

Figure 2. A schematic diagram illustrating how the path length of radiation through the Earth's atmosphere depend on altitude.

8-2.2 The Sun's atmosphere

The layers above the photosphere comprise the Sun's atmosphere. The atmosphere is usually divided into two main parts, the chromosphere and the corona. The chromosphere is a rather shallow layer compared with the corona. Most of the absorption lines seen in the Sun's spectrum are produced by the chromosphere. The spectral lines are broadened indicating that there is turbulence in the chromosphere. The spicules, which are seen on the limb of the Sun, extend up into the corona. It is believed that the spicules are the granules seen edge on.

The corona is a very extensive layer that has a kinetic temperature in excess of a million Kelvins but is of very low density. It is not yet fully understood how the corona is heated, though more recent investigations indicate that magnetic field lines play a role.

8-2.3 The Internal Structure of the Sun

The Convective Zone is a region in the Sun from about $0.87R_\odot$ to the surface. In this layer, energy transport from the interior layers to the photosphere is mostly by convection. Convection occurs because the opacity of this layer is higher than the layer below.

The Radiation Zone extends from about $.25R_\odot$ to $0.8R_\odot$. In this region energy transport from the core is mostly by radiation. This is because the opacity in this region is low because of the higher temperatures result in a high degree of ionization. Therefore, the electrons are free of their atoms and can only scatter the radiation but not absorb it.

The Core of the Sun is where thermonuclear fusion reactions occur. These reactions supply the energy that keeps the Sun shining at a rate that it has been shining for the last 4.5 billion years. The main reaction occurring here is the proton-proton chain that converts protons into helium nuclei (alpha particles). See P5-7 in Z&G.

8-3. Solar Radiation

The Sun emits radiation of different intensities in different regions of the spectrum. In general, the radiation of the Sun has a spectrum similar to that of a blackbody at a temperature of 5800 K. There are numerous absorption lines that were first measured by Fraunhoffer in 1814.