28.1 Introduction

A striking aspect of photographs of the Sun is the darkening of the solar image toward the limb (see Fig. 28.1). The decrease in brightness, which is accompanied by a reddening of the solar image in color photographs, is not uniform. Near the center of the disk the change in brightness is small but within a few arc seconds of the limb the brightness falls off so steeply that the edge of the solar disk appears sharp. This is the *limb darkening* of the Sun, sometimes called the *center-to-limb variation*. An incandescent solid, on the other hand, will have a constant surface brightness. A glowing tungsten or platinum wire, for example, shows no limb darkening. Limb darkening is the most visible sign of the gaseous nature of the outer layers of the Sun.

The solar atmosphere consists of three regions: the photosphere, the chromosphere, and the corona. The *photosphere*—literally the sphere of light—contributes most of the light that we see in the visible disk of the Sun. The temperature of the photosphere amounts to \( \sim 6100 \) K at disk center but only \( 5770 \) K averaged over the disk (due to limb darkening). In sunspots, like those seen in Fig. 28.1, the temperature lies about 1000 K lower. Like the solar limb, the sunspots would appear bright if seen projected against the sky; they are dark only in contrast to the brighter, unspotted, disk center.

The layer above the photosphere is the *chromosphere*, the sphere of color, a name derived from its appearance during total solar eclipses. Its narrow, irregular red rim around the darkened disk of the Sun has been compared to a prairie fire. The red color is due to the emission of hydrogen \( \alpha \) (the Balmer \( \alpha \) line, marking the energy transition between the third and second energy levels of the hydrogen atom), although the other Balmer lines are visible spectroscopically. Except in these lines, in the visible region of the spectrum, the optical depth in this region is low. The thickness of the chromosphere is very thin—only about 7000 km compared to the solar radius of 700,000 km—but throughout this relatively thin region, the temperature rises rapidly from a temperature minimum (\( \sim 4200 \) K) until it reaches the temperature of the solar corona. For this reason, the upper chromosphere is sometimes referred to as a transition region.

The *corona* is the overlying region of high temperatures (\( \sim 2 \cdot 10^6 \) K) and very low densities (particle densities are only \( \sim 10^{12} \) m\(^{-3} \) compared to photospheric values \( \sim 10^{23} \) m\(^{-3} \)). The high temperature explains why the corona extends to several solar radii, and it explains as well the appearance in the spectrum of the extremely high ionization stages of atoms [e.g., Fe XIV – an iron atom ionized 13 times]. The photospheric Fraunhofer lines reflected from the dust component of the corona (the F corona) also show the effects of those high temperatures in the great broadening of the lines by the rapid Doppler shifts of the atoms and electrons. Yet despite the very high temperatures and huge physical extent, the optical depth (outside of the emission lines, in the visible part of the spectrum) is very low. The pearly light of the corona is visible only during an eclipse (although this may be simulated by an occulting disk at a high-altitude site or from space), and its total light amounts to only as much as that of the full Moon. The light of the corona has a peculiarly structured appearance—coronal plumes—controlled by magnetic fields. Since the magnetic field structures undergo changes through the solar cycle, the shape of the corona varies from maximum to minimum along with the level of solar activity. Condensations of higher density in the corona,
28.2 The Photosphere Explored

Through Limb Darkening

The passage of radiation through layers of gaseous atmosphere is connected to the absorption and emission coefficients of the gas. The absorption coefficient, \( k_\lambda(r) \), is a function of the wavelength (indicated by the subscript) and of the depth to which we see into the atmosphere, \( r \). Generally, it increases inward from the solar radius toward the center and essentially describes the power of a cross section of matter to absorb energy. The total amount of energy removed from a beam depends on the physical extent of the gas, hence the use of the notion of optical depth, \( \tau_\lambda \) (introduced in challenge 2 of §19.5, on the astronomy of fogs and mists). In the case of the penetration of light through a terrestrial fog, \( \tau_\lambda \) can be written

\[
\tau_\lambda = \int_{r=0}^{r=R} k_\lambda(r) \cdot dr \quad (28.1)
\]

The use of integration should be familiar at this point. Equation 28.1 can be thought of as merely the addition of the areas of many narrow rectangles of width \( dr \) and height \( k_\lambda(r) \) over the range of \( r \) from 0 to \( R \). When \( k_\lambda \) is constant, Eq. 28.1 becomes

\[
\tau_\lambda = k_\lambda \cdot R
\]

The depth to which one can peer into the solar atmosphere is obtained by similar reasoning. The process of absorption must be balanced by the process of reemission. The reemission process is somewhat analogous, but in the case of the fog, the absorption is actually produced by the scattering of light out of the beam, and the radiation scattered by a fog volume element of size \((1 \text{ m}^3) \cdot dr\) is proportional to the "absorption coefficient." Similarly, the corresponding emission volume element in the solar atmosphere produces, according to Kirchhoff’s law, an amount of radiation proportional to \( k_\lambda(r) \). The emissivity is given by

\[
\varepsilon_\lambda = 1 \text{ m}^2 \cdot B_\lambda(T) \cdot k_\lambda(r) \cdot dr \quad (28.2)
\]

where \( B_\lambda(T) \) is the Planck function (or sometimes, the Kirchhoff-Planck function). Because \( T, r, \) and \( \tau_\lambda \) all increase inward, \( B_\lambda \) can be considered a function of \( \tau_\lambda \). Therefore, Eq. 28.2 can be rewritten:

\[
\varepsilon_\lambda = (1 \text{ m}^2) \cdot B_\lambda(\tau_\lambda) \cdot d\tau_\lambda \quad (28.3)
\]

To avoid rewriting the volume element each time, we hereafter assume that the emissivity is given in SI units per square meter.

The effects of absorption and emission processes on a beam of radiation emerging from the outer layers of the photosphere are sketched in Fig. 28.2. At the upper boundary, the contribution to the intensity of radiation per square meter may be summed up in the following integral:

\[
I_\lambda = \int_{r=0}^{r=R} B_\lambda(T) \cdot k_\lambda(r) \cdot \exp[-\int_{s=0}^{s=r} k_\lambda(s) \cdot ds] \cdot dr
\]

or

\[
I_\lambda = \int_{\tau=0}^{\tau=\infty} B_\lambda(\tau_\lambda) \cdot e^{-\tau} \cdot d\tau_\lambda \quad (28.4)
\]

Mathematical techniques permit a run of values of \( k_\lambda(r) \) and \( T(r) \) to be traced back from measured

\[1\text{We must recognize from the existence of spectral absorption lines that it may not look that way when there is a flux of radiation through a gas. When the radiation emitted in all directions is taken into account, there is a balance between total absorbed and total emitted photon energy. If there was not, the atmosphere could not be considered stable. Such instabilities are found in pulsating and eruptive variable stars.}\]