Chapter 3

Studying the Sun

We see the Sun because of the radiation that leaves it and arrives at Earth after about 8 minutes of travel through space. Until the 1940s, we had only seen the Sun in the visible range, which gives us a look at the photosphere and low chromosphere where most of the visible light is produced. But as we began to look at the Sun in other wavelengths, by devising appropriate sensing devices like x-ray telescopes, a new and vastly more detailed picture of the Sun emerged. Each type of radiation—radio, infrared, visible, ultraviolet, x-ray, and gamma—originates predominantly from a different part of the Sun. The different layers, from the photosphere up into the corona, can be seen by looking in different specific wavelengths; each layer reveals different secrets of the complex and turbulent Sun. ***Magnetograms***—pictures of the magnetic field regions of the sun—give us another view of the Sun, which suggests that the driving mechanism in the solar atmosphere is the magnetic field. The contorted, dynamic magnetic fields emerging from the photosphere and chromosphere have a seemingly infinite complexity. Today it is clear that all of the processes occurring on the Sun are beyond our present knowledge. Developing a model for the Sun is truly a new frontier.

Section 1.—White Light: The Photosphere

The light that illuminates our world and enables us to see things with our eyes comes from the photosphere of the Sun. To most of us, the photosphere is the Sun. Most of the energy that we receive from the Sun is the visible, or ***white light*** that radiates from the thin, relatively cool photosphere. The photosphere is the region of the Sun where emitted photons are able to escape into space, rather than being scattered or absorbed as they are in layers. At a mere 6000 K, it is one of the coolest parts of the Sun; it has a thickness of only about 100 km, or about 0.1% of the solar radius.

The visible radiation produced in the photosphere is characteristic of matter at a few thousand kelvins, undergoing atomic-energy-level transitions. The matter in the photosphere is a plasma, with a high degree of dissociation of electrons from nuclei, resulting in charged particles. But the plasma of the photosphere is cool enough that it is largely in an ***atomic state***, much like the matter we are used to on Earth. This means that nuclei have electrons in orbit, although outer electrons are missing, and the orbiting electrons are making transitions down to lower energy levels, producing photons of light. When broken apart with a spectroscope, the white light from the photosphere makes a continuous spectrum of wavelengths, interrupted by absorption lines. The spectral line signature of virtually every element has been detected in this white light, but by far the most abundant elements in the solar atmosphere are hydrogen (92%), and helium (7.8%). The Sun seems to follow the cosmic recipe found all over the universe of 10 parts hydrogen to 1 part helium with a pinch of every other element. The most common trace elements are oxygen, carbon, nitrogen, iron and magnesium.

Using proper filters the photosphere can be seen to have a granular appearance with a mixture of brighter and darker spots. These regions are the tops of convective cells, with bright areas resulting from hotter plasma bubbling upward and the darker regions caused by cooler plasma sinking into the interior. The large scale convective patterns within the Sun are thought to be closely tied to the magnetic effects seen in the photosphere, and in the associated sunspot regions.

Section 2.—Sunspots

After the dazzling brightness of the Sun, its next most obvious feature is the appearance of sunspots on the photosphere. Sunspots have been reported for more than 2000 years, and were probably seen in early times when the solar disk was darkened near sunrise or sunset, or by the smoke of a volcanic eruption. Throughout most of history the Sun has been a symbol of purity. Within this context, Galileo's report of sunspots, observed with an early telescope around 1610, was not taken well by the Church and other protectors of the status quo. There was much speculation about what these blemishes were, including that they were planets or other objects passing in front of the Sun.

As telescopes improved, Galileo and others found that sunspots have a dark central region, called the ***umbra*** (shadow), surrounded by a lighter region, the ***penumbra***. Observations over many days soon revealed that the spots move across the Sun as the Sun rotates and that the equatorial region moves faster than the higher latitude regions. Sunspots were also observed to grow in clusters over several days or weeks and then gradually disappear. For reasons not yet understood, there were very few sunspots from about 1645 to 1715. This ***Maunder Minimum***, as it is now called, coincided roughly with a very cool period in Europe, and this has raised the possibility of a connection between sunspot activity and climate on Earth.

When sunspot activity returned in about 1715, Sun observers began to keep records of sunspot numbers. In 1843, an amateur astronomer named Heinrich Schwabe studied these records and noticed that sunspot numbers reached a maximum every 10 to 12 years, and nearly disappeared in between these periods. This sunspot cycle is now well documented over the last 200 years. Solar cycles from 1900 to 2015 (Figure 3-1) illustrate the variances from one cycle to another, not only in sunspot numbers, but also reveal a double peak of activity in recent years.

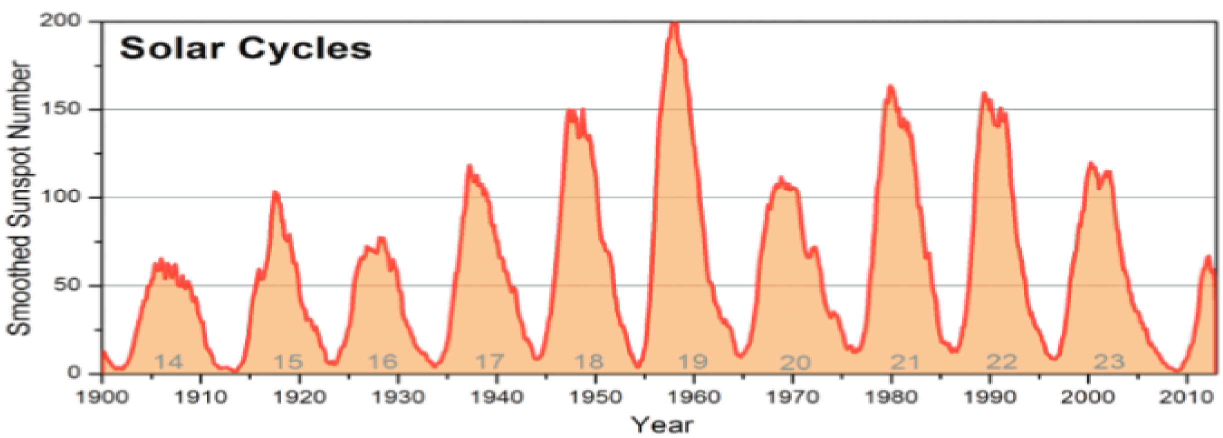

Figure 3–1.—*Sunspot Cycles from 1900 to 2015. One periodic increase and decrease of sunspots defines a cycle. Cycle 23 began in 1996, peaked in 2000 and ended in about 2008.*

Beginning with the minimum that occurred around 1755, sunspot cycles have been numbered; for example solar cycle 24 began with the 2008 minimum and had two peaks, the first in about 2011 and the second in early 2014 (Figure 3–2). This sunspot behavior reveals how scientists still have many questions about sunspots—their origin, their behavior, and their relation to flares. Most flares originate in the active regions which usually surround sunspots, but as yet it is still very difficult to predict when a flare will erupt.

Sunspots are cooler than the surrounding photosphere by about 1800 K. At about 4200 K, they are the coolest part of the Sun. This lower temperature is thought to be due to a lack of convection which brings hotter plasma to the surface. Seen from the side as they appear or disappear around the limb of the Sun, it is clear that sunspots are depressions in the photosphere.

In 1908, George Hale discovered that sunspots had strong magnetic fields associated with them. He concluded this when he observed the newly discovered ***Zeemann effect*** in the spectral lines of light emitted from sunspots. The Zeemann effect is a splitting of spectral lines that occurs when the emitting or absorbing atoms are immersed in a magnetic field. The Zeemann effect is still used today to make magnetic pictures, or magnetograms, of the Sun. The

Solar Cycle 23 Sunspot Peak through Solar Cycle 24 Sunspot Peaks

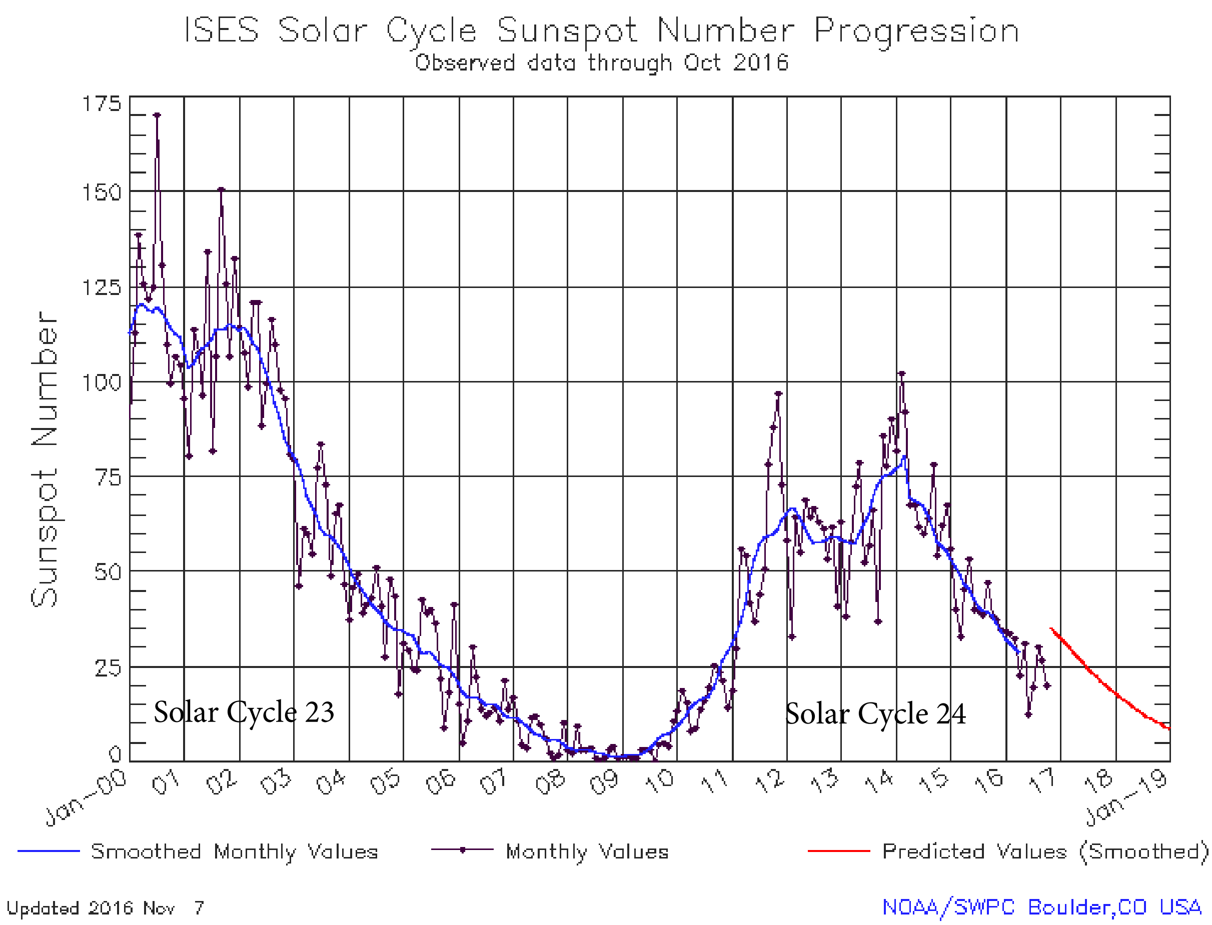

Figure 3–2.—*This SWPC plot shows the actual monthly mean total sunpot numbers, along with a smoothed monthly sunspot value from January, 2000 through October, 2016. These types of plots can help scientists predict how large a current cycle will be or is progressing in relation to a solar cycle forecast.*

strong magnetic fields of the sunspots are of two types, either straight out (+ polarity) or straight in (– polarity). This may be thought of as a north or a south pole. Within sunspot groups, sunspots often come in pairs with opposite polarity. In many cases the field lines connect the two sunspots, arching over from one to the other (Figure 3–3).

Hale also discovered that the 11-year sunspot cycle is part of a 22-year solar magnetic cycle. He found that sunspots usually come in pairs, with the leader (the one first carried across the solar disk by rotation) having a magnetic polarity opposite from that of the following spot. Leader spots in the northern hemisphere tend to have a polarity opposite that of the leader spots in the southern hemisphere. This reverses itself with each solar cycle, so that leader spots in the northern hemisphere will have a polarity opposite the leader spots from the previous cycle. It therefore takes about 22 years for this cycle of magnetic polarity to repeat itself. We now know that the Sun's polar magnetic field reverses every 11 years, and is closely tied to the 22-year sunspot polarity cycle.

In the early years of a sunspot cycle, sunspots tend to be smaller and to form at higher latitudes, both north and south. As the cycle proceeds toward a maximum, the spots generally become larger and form closer to the equator. Near the time

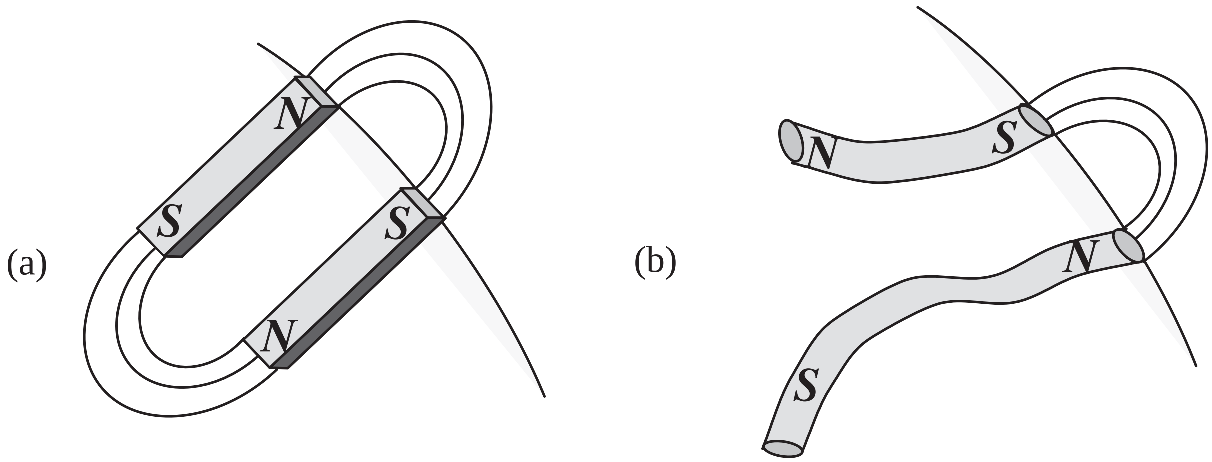

Figure 3–3.—*(a) A pair of bar magnets submerged below the photosphere would produce fields at the surface resembling those of an active region near sunspots. (b) More realistically, flexible magnetic tubes, or flux tubes, probably give rise to the magnetic fields that we see.*

of the sunspot maximum, spots are most likely to form at latitudes of 10° to 15°. As the cycle subsides toward a minimum, the spots get smaller and appear closer to the equatorial region. There is an overlap of the end of one cycle and the beginning of the next, as new spots from the next cycle form at high latitudes while spots from the present cycle are still present near the equator. Recently, it has been discovered that the high-latitude spots of a new cycle have a predecessor, known as ephemeral regions, which form at very high latitudes near the time of the maximum of the previous cycle. This general drifting of sunspot appearance from high latitudes toward the equator was first discovered by Edward Maunder in 1904, when he plotted the latitude of sunspots over many cycles (Figure 3–4). It is not yet known why sunspots migrate in this way, but we suspect that a number of different interior convective and rotational processes determine where magnetic flux emerges and how it becomes organized into sunspots.

A strong correlation has been established between sunspots and solar flare activity, with more numerous and energetic flares found near the larger and more complex types of sunspot groups. Because flares can have such an adverse effect on our technical systems on Earth, there is great interest in predicting when flares will occur and how large they will be. Sunspot observations provide one of the best tools for flare prediction and there have been many attempts to classify sunspots according to their likelihood of producing flare activity. The earliest such classification was devised by Cortie in 1901. This system was modified by Waldmeier, in 1947, into what is referred to as the ***Zurich system*** of sunspot classification. The Zurich system was found in the 1950s and 60s to still be too simple for effective flare prediction. Highly experienced sunspot watchers, including Patrick McIntosh at the NOAA Space Environment Lab in Boulder, began to notice structural and dynamic aspects of sunspot groups that correlated well with flares but were not a part of the Zurich classification. Some of these missing parameters were incorporated into a revision of the Zurich system and introduced by McIntosh in 1966. The ***McIntosh Classification system*** has 60 types of sunspot groups and has been widely used ever since. Additionally, the ***Mount Wilson Sunspot Magnetic Classification system*** is used to assess and categorize the magnetic complexity of sunspot groups. The McIntosh classification system is used in conjunction with the Mount Wilson Sunspot Magnetic classification system in order for space weather forecasters to better codify and track changes in sunspot group complexity. A relationship often exists between sunspot regions' classifications to flare intensity and potential. These classification schemes provide a means for forecasters to track regions' changes and aid in the ability to predict flares, especially when used in conjunction with other available information sources like x-ray activity, radio emission levels, and magnetograms.

Flares are likely to erupt in large sunspot regions that are growing rapidly and rotating like hurricanes. Flares can also arise in areas far from sunspots, and sometimes large sunspot areas produce very little flare activity. At present, we are

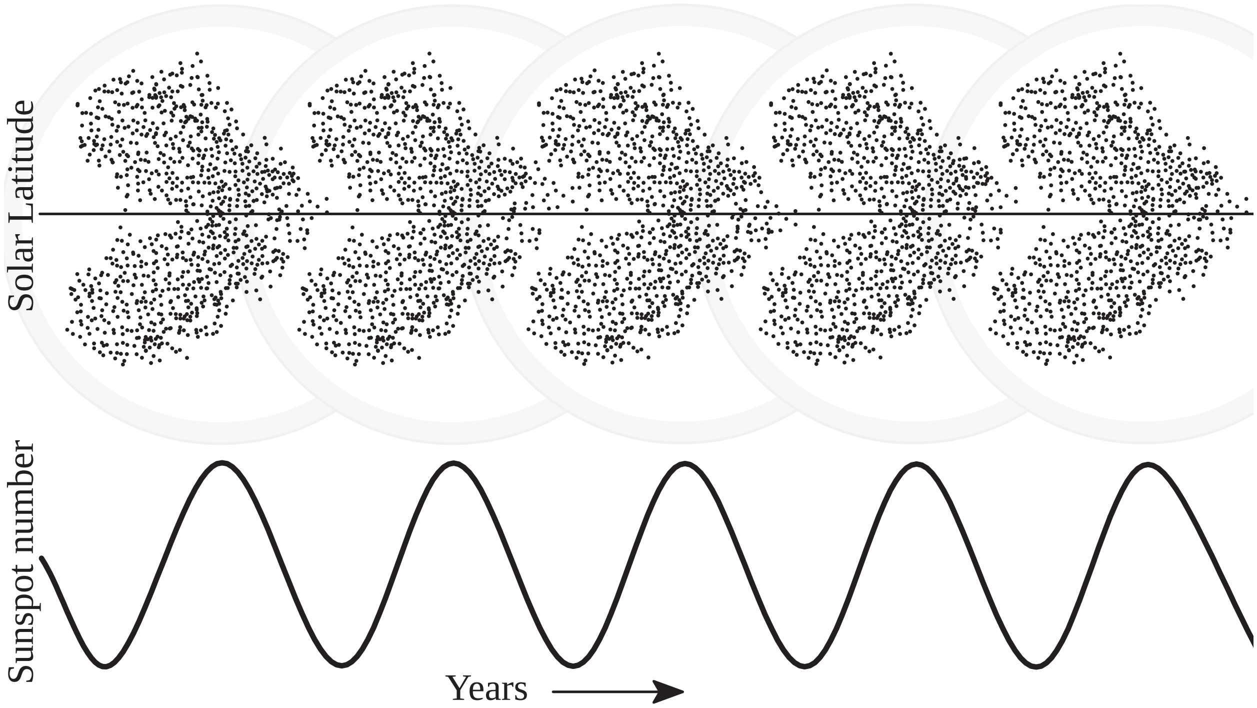

Figure 3–4.—*A schematic illustration of the migration of sunspots from higher latitudes toward the equator during each cycle (shown schematically below) is seen in the characteristic "butterfly" pattern. The overlap of the end of one cycle and the beginning of the next can also be seen.*

fairly good at predicting where flares will erupt, but not very good at predicting when they will occur. A deeper understanding of sunspots is certainly required before our flare prediction can be accurate.

Section 3.—Hydrogen-Alpha: The Low Chromosphere

By the early 1800s, scientists had begun to explore the nature of light by breaking it up into its component spectrum of wavelengths. The spectral analysis of light from different flames revealed that each element produced a unique set of wavelengths, or spectral lines. The explanation for this would not come for another 100 years, with the Bohr model of the atom and the idea of transitions between atomic energy levels. Nonetheless, early spectroscopists could identify elements from the light they emitted, and astronomers began to look at the light of the Sun with spectroscopes. The spectral lines seen in sunlight were similar to those seen in the light from laboratory sources on Earth, and so the chemical composition of the Sun could be surmised. Around 1814, Joseph Fraunhofer noticed that there were dark lines in certain places on the bright emission spectrum from the Sun (Figure 3–5). He did not understand what caused these dark lines, but he mapped the most prominent ones and labeled them simply A, B, C, and so on. By 1859, Gustav Kirchhoff had discovered in his experiments that these dark lines, now called ***Fraunhofer lines***, were caused by the absorption of light as it passed through a vapor of atoms. He suggested that the white light being emitted from the photosphere must be passing through a cooler layer that was absorbing particular wavelengths characteristic of the elements in that cooler layer.

In 1885, Balmer completed a detailed study of the spectrum of visible light produced by hydrogen. The hydrogen spectrum had a very distinctive pattern of lines crowding closer and closer together toward shorter wavelengths. Balmer was able to find an equation which accurately gave the wavelengths of these visible lines, now called the ***Balmer Series***. The longest wavelength line in the Balmer series—the α line—is red with a wavelength of 656 nanometers, and this line is seen prominently in the solar spectrum. In 1913 Niels Bohr was able to explain the Balmer

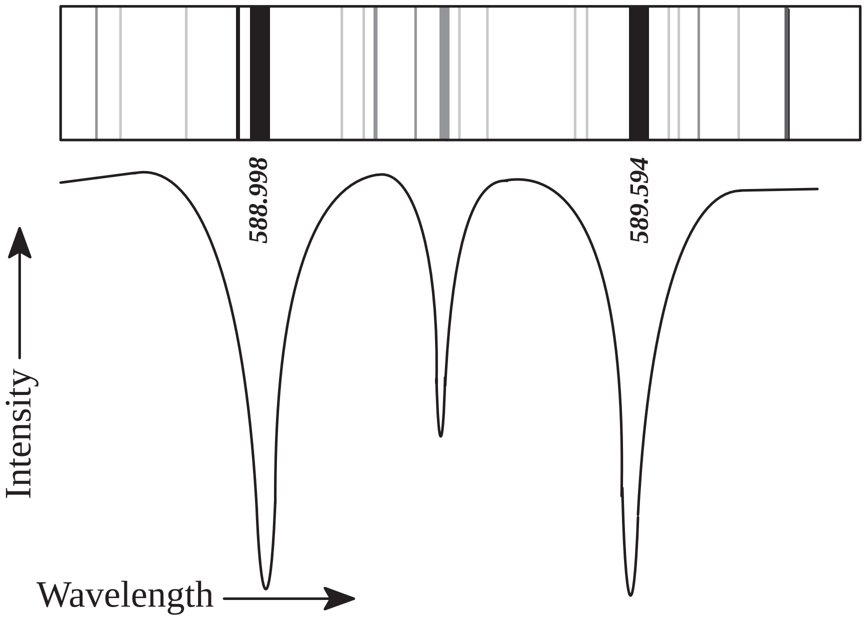

__Figure 3–5.__—Schematic of Sodium absorption from a Solar white-light spectrum. Top: The two dark absorption lines with wavelengths of 589.0 and 589.6 nanometers are produced by sodium atoms absorbing at these wavelengths. Fraunhofer observed these two lines as one, which he named the "D" line. Bottom: The same spectrum as seen on a graph of intensity versus wavelength. Each dark line appears as a drop in intensity, where light is subtracted from the continuous spectrum.

lines as transitions within the hydrogen atom. The Balmer series, which is the visible part of the hydrogen spectrum, results from transitions ending at the first excited state.

By 1891, George Hale and Henry Deslandres independently realized that the red hydrogen-alpha (Hα) line was an important clue to the Sun's nature. They began to look at the Sun in a very narrow band around 656 nm with a device called a ***spectroheliograph*** that isolated light from one spectral line. Eventually Hale was able to make photographs of the entire solar disk using only light at the Hα wavelength. Because this wavelength of light is being emitted by the chromosphere, Hα photographs are pictures of the chromosphere. By the 1930s astronomers had taken many photographs of the Sun in the Hα, and a new description of the Sun began to emerge.

The features of the chromosphere revealed in the Hα are very different from the features of the photosphere seen in white light (see Figure 3–6). The chromosphere is covered with bright and dark areas that change from day to day; vivid, string-like ***filaments*** appear and disappear in unpredictable ways. Sunspots are seen in the Hα as the absence of light, and the features and activity of the chromosphere are obviously linked to the underlying sunspots. The strong magnetic flux that emerges from sunspots arches up into the chromosphere, and flares seem to be triggered when these fields buckle and change. The active regions around sunspots show up as bright plages in the Hα, and flares occur almost exclusively in these areas of plage above large and complex sunspot groups (Figure 3–7).

Because the Hα picture of the Sun is so useful in predicting eruptions, scientists at NOAA and at observatories around the world are constantly watching the Sun at this wavelength. Today, astronomers use filters made of a sandwich of thin films to view the Sun in the Hα. These filters can be tuned to wavelengths other than the 656 nm Hα, and slightly different wavelengths give a picture of the Sun at different depths in the chromosphere.

The filaments seen on the chromosphere are actually more like "floating fences" about 50,000 kilometers tall. They float above the photosphere, much like clouds floating above the Earth's surface, and then disappear either by dissipating (as Earth clouds often do) or by suddenly rising upwards to become a prominence. Magnetic field pictures

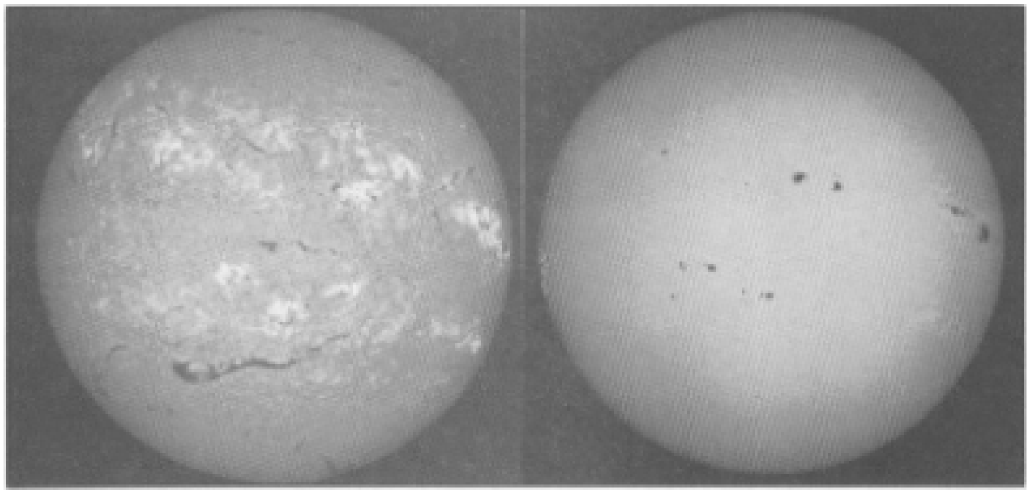

Figure 3–6.—*Two views of the Sun, one photograph taken in white light, one taken in Hα*

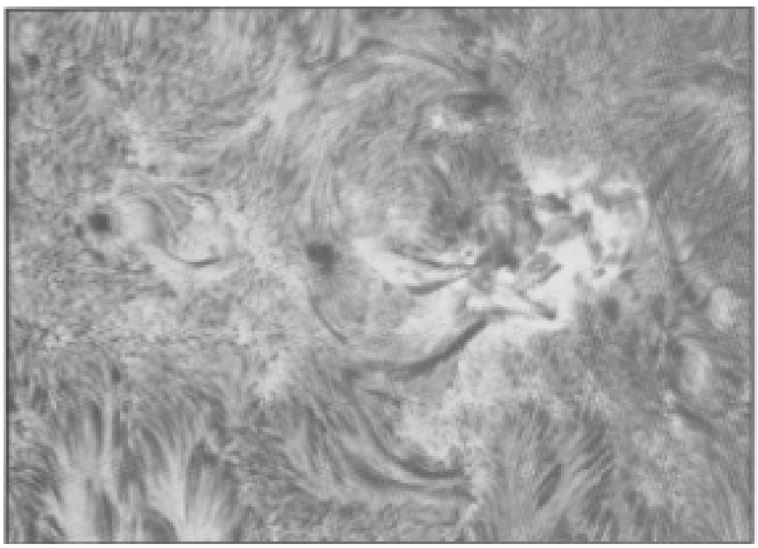

Figure 3–7.—*A close view of the low chromosphere taken in the Hα depicting the fibril structure around a solar region. The bright areas of plage lie above the sunspots on the photosphere. Photo courtesy of Big Bear Solar Observatory.*

of the Sun reveal that filaments form along the boundaries between regions of positive and negative magnetic polarity on the Sun. These boundaries, called neutral lines, run all over the solar surface. It is not known why filaments form on some neutral lines but not others, but filaments are generally of interest because they are a common source of eruptions. Solar physicists have constructed maps of the solar surface showing the locations of active regions, neutral lines, filaments, and coronal holes for each month during the last 20 years. Looking at how these features appear, move, and disappear will undoubtedly give us more understanding of the physics of the Sun.

Section 4.—Ultraviolet: The High Chromosphere

Pictures of the Sun at ultraviolet wavelengths were not possible until space-based instruments could be used, since our atmosphere blocks most of the ultraviolet radiation. During 1973 and early 1974, the three ***Skylab*** missions made extensive observations of the Sun in ultraviolet light and x-rays, which brought an avalanche of new knowledge about the Sun (see Figure 3–8). Skylab was a low-orbiting space station that could hold a crew of three astronauts.

Skylab was equipped with a variety of instruments for studying the Sun in ultraviolet, x-ray, white light, and Hα light. The three missions, which lasted 28 days, 59 days, and 84 days, were among the most scientifically significant

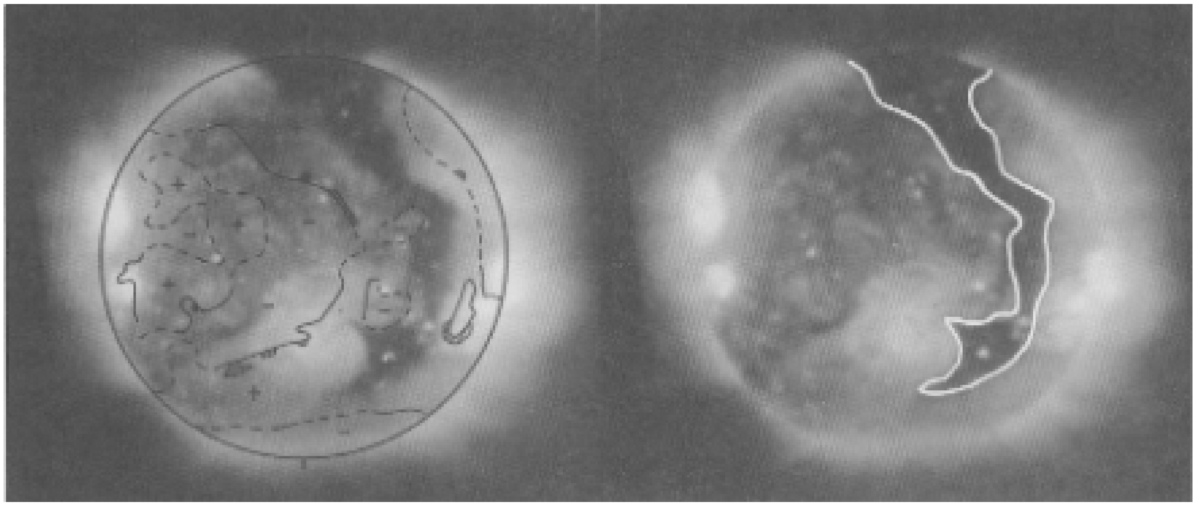

Figure 3–8.*—An x-ray image of the Sun taken during the Skylab mission on June 30, 1973. The right photo shows a coronal hole outlined in white. The large boot-shaped coronal hole stretches from the north pole into the southern latitudes. The left photo shows the lines of reversal in polarity of magnetic fields. The coronal hole lies in the middle of a large unipolar area of positive polarity.*

accomplishments of our space program to date. The vast amount of data collected by Skylab brought about a huge leap in our understanding of the Sun. Ironically, Skylab itself was a victim of solar activity. Its orbit decayed rapidly as Earth's atmosphere heated and expanded because of high activity levels on the Sun; Skylab fell to Earth in 1979. Since that time, we have had limited capability to collect ultraviolet data because government priorities have shifted away from the launching of research satellites.

The ultraviolet radiation that the Sun emits comes from the upper chromosphere, which is at a temperature of around 70,000 K. To some extent, the type of radiation produced by each region of the Sun may be thought of as corresponding to the temperature of that region. A plasma emits radiation as a ***blackbody***, producing a broad spectrum of wavelengths (Figure 3–9). However, any blackbody has a peak at a certain wavelength that is determined by the temperature, and it will produce radiation predominantly in this wavelength. Although each region of the Sun emits virtually all types of

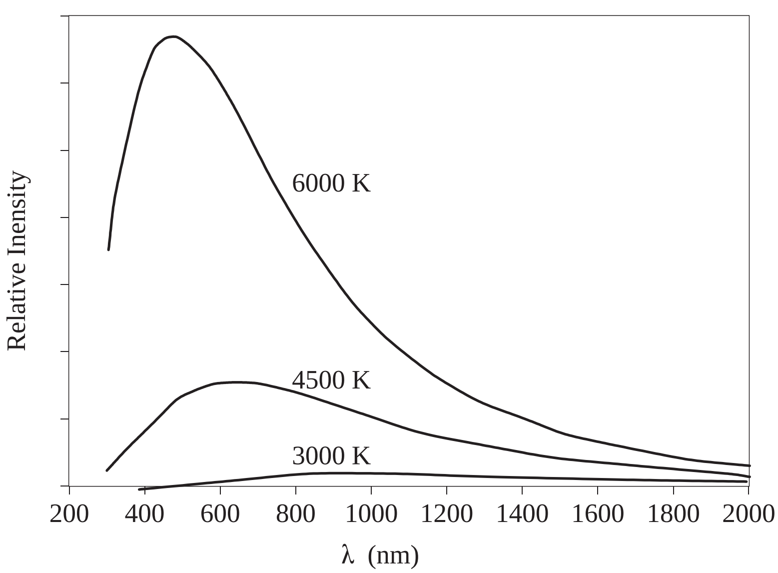

Figure 3–9.*—Schematic blackbody radiation curves at three temperatures. The wavelength of maximum intensity varies inversely with the absolute temperature as in the formula*

$$\lambda_m = \frac{C}{T}$$

radiation, from radio to x-ray, there is a predominance of one type of radiation that is determined by the temperature of the region. The coolest region of the Sun is the low chromosphere, and it produces mostly the reddish Hα wavelength. The slightly hotter photosphere produces all of the visible wavelengths. Hotter still, the high chromosphere produces mostly ultraviolet, and the very hot corona is most intense in x-rays.

Ultraviolet pictures of the high chromosphere show several prominent features that are not very evident at other wavelengths. A mottled network, known as the chromospheric network, covers the entire solar disk except the area near the poles. This mottling is thought to be caused by convective cells, which dominate the chromosphere at this height. The Skylab data revealed an excellent picture of spicules—small, flare-like eruptions that occur all over the upper chromosphere. The top of the chromosphere is much like the top of the ocean, with waves erupting upwards. Spicules are part of the "quiet Sun" activity, and though they are considered to be small they are typically about the size of Earth. It is thought that spicules may play a crucial role in the formation of giant prominences as they feed material upward into the corona. The Skylab data also showed that there are very few spicules near the poles, but they are much larger. A much better picture of the polar regions was seen from the Skylab observations, and it was confirmed that long-term coronal holes reside near the poles. Coronal holes can have a dramatic effect on Earth since they are a major source of the solar wind.

Section 5.—X-rays: The Solar Corona and Beyond (Solar Wind)

The solar corona, at temperatures of one to two million K, emits a wide range of radiation. As early as 1869, C.A. Young observed a green line in the coronal spectrum during an eclipse. In the following decades other visible lines were seen in the corona, lines that were not present in the light from the chromosphere or photosphere. Because these emission lines had never been seen in the spectra of the known elements it was thought that a new element, called ***coronium***, must be present in the corona. It was not until 1940 that Edlen showed these lines to be the result of transitions in highly ionized elements like iron and calcium. This degree of ionization happens only at very high temperatures. At about 2 million K iron has lost 13 of its 26 electrons and at 20 million K it has lost 22 of 26 electrons. The spectral lines that result from these highly ionized states can be used to estimate the temperature of the corona. For example, the yellow line emitted by 14-times ionized calcium is most abundant at 4 million K. The green line seen in 1869 is produced by 13-times ionized iron at about 2 million K. These very high temperatures are not as extreme as they sound because the mass in the corona is so diffuse. The total amount of energy emitted by the corona is small compared to that coming from the denser lower atmosphere.

When we study the corona in visible light, we are really not looking at the right wavelength. The amount of visible light is small because there are so few atoms scattering the light, and this weak light is overwhelmed by the very much brighter surfaces below. The corona is much more efficient at emitting high-energy, short-wavelength radiation such as the extreme ultraviolet (EUV) and x-rays. In 1946, a V2 rocket launched to the modest height of 90 km captured the first glimpse of the Sun in the EUV. Such rocket flights were limited by the short time aloft, but, by 1958, orbiting satellites with small-sized instruments became a reality. A major breakthrough came with the Skylab missions in 1973, which allowed the astronomer-astronauts to photograph the sun at x-ray wavelengths with large and sophisticated instruments. The corona came alive with previously unknown features: bright beacon-like active regions, dark coronal holes, short-lived bright points, and huge magnetic arches that dominate the overall structure of the corona.

X-rays are produced in the corona by the accelerated motion of electrons in the coronal plasma and not by atomic energy level transitions. These high-speed electrons interact with positive ions in the plasma by slowing down, speeding up, or curving. They are rarely captured into orbits because they are moving so fast due to the high temperature of the corona. When flares erupt, electric fields accelerate electrons upward so that they reach speeds close to the speed of light in a short time. This positive acceleration is relatively low and does not produce any measurable radiation. The electrons then arch back and return to the Sun, crashing violently into the denser material of the chromosphere. It is this rapid deceleration of electrons which produces the sudden burst of x-rays that accompany flares. X-rays produced by a rapid deceleration are referred to as ***Bremsstrahlung*** (German for "braking rays") ***x-rays***. X-ray images of the Sun (Figure 3–10) reveal the structure and behavior of the corona. The x-ray emission is brighter where the coronal plasma is hotter and more dense. Flares are usually first detected here on Earth from the rise in x-ray flux, and for this reason the monitoring of the Sun at x-ray wavelengths has a high priority. At the present time, the Sun is continually monitored in the x-ray wavelengths by NOAA weather satellites called Geostationary Operational Environmental Satellites (***GOES***).

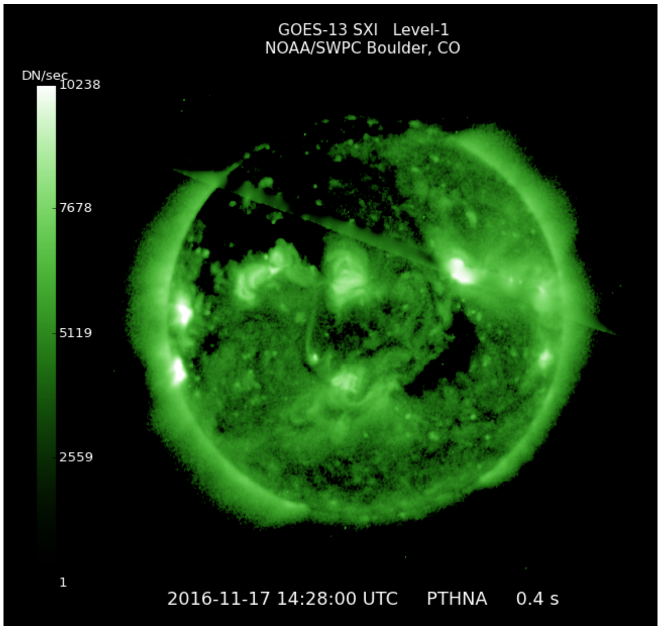

Figure 3–10.—*An x-ray image of the Sun taken in 2016, from the GOES-13 solar x-ray imager (SXI). Various exposure settings are captured throughout a sequence of images taken each minute. This particular image (Level-1) allows a better look at coronal structure; as well as some examination of active regions and flares.*

There are two main geosynchronous orbital locations occupied by GOES satellites in order to cover the meteorological needs of North America, to include the east Pacific and west Atlantic oceans; they are GOES west (about 135W-137W) and GOES east (about 75W). Space weather packages on these platforms monitor the Sun and the near-Earth space environment with x-ray and energetic particle sensors, and magnetometers. Unfortunately, satellites such as these have limited lifetimes as their orbits drift. Some become unusable over time as sensors go bad or their location wanders too much from the proper "stationary" location. Early in their lifetime, orbital corrections can be made by on-board thrusters; but eventually the fuel for these runs low and they need to be replaced. The GOES satellites comprise a "constellation" and the latest platforms are expected have an operational lifetime through the year 2036. The GOES satellites' raw data are downlinked to antennas in Boulder, CO and processed at SWPC.

The primary x-ray wavelength monitored for flare activity is 1 to 8 Angstroms. When a solar flare occurs, the x-ray level (flux) rises dramatically. When the x-ray flux rises above a certain threshold, alerts are immediately transmitted by SWPC forecasters to customers all over the world. The x-rays leaving the site of a flare travel at the speed of light and take approximately 8 minutes to reach Earth. Larger flares from favorable locations may on rare occasions accelerate quantities of energetic particles from the Sun that can arrive to Earth within 15 minutes to some hours later. Proton flux is monitored for these particles and when it appears that specific thresholds are expected to be reached, warnings are sent out.

Additional satellites have been placed into orbits that allow monitoring of the Sun and the space environment to include: DSCOVR (Deep Space Climate Observatory), a NOAA operational satellite placed in an orbital area that keeps it directly between the Sun and the Earth, about 1 million miles from Earth known as L1. This platform measures the solar wind environment (speed, density, temperature, and interplanetary magnetic field (IMF) parameters) and acts as a kind of observational "space bouy" for conditions soon to arrive at Earth. DSCOVR is critical to SWPC forecasters ability to monitor solar wind conditions real-time and warn of impending geomagnetic storms. SOHO (Solar & Optical Heliospheric Observatory) is a NASA research satellite also located at L1. The SOHO LASCO instrument (Large Angle & Spectrometric Coronagraph) takes periodic images of the Sun's corona using an occulting disk that allows a visual look at the outer corona at different distances from the Sun. The two most used by forecasters are the C2 (1.5 to 6 solar radii) and C3 (3.5 to 30 solar radii) coronagraphs. The LASCO instrument is crucial for identifying large expulsions of plasma from the Sun known as ***coronal mass ejections*** (***CME***); often associated with solar flares or filament eruptions. Forecasters examine LASCO imagery for indications of CMEs and when detected, analyze them using computer tools and models to help determine if they may be Earth-directed, and if so, predict timing of arrival and issue geomagnetic storm watches up to three days in advance.

Section 6.—Radio Emission: Solar Flares

Radio astronomers have been monitoring the Sun in the radio wavelength range since the 1940s. The Sun is a very “noisy” radio source, meaning that it produces a wide range of radio emissions on a steady basis. Unlike the ultraviolet and x-ray emissions, radio waves generally do penetrate Earth’s atmosphere, so they can be picked up with ground based instruments. These radio telescopes have large parabolic collecting areas for concentrating weak signals. The radio range is extremely broad, from long waves that have wavelengths of thousands of kilometers to microwaves with wavelengths of a few millimeters. Much of the study of the Sun in the radio range has been done at a wavelength of 10.7 cm, but today there is extensive monitoring down to wavelengths of a few millimeters. It is believed that these short radio waves (or microwaves) are produced by charges in circular motion during a flare. Radiation produced by charges in circular motion is often referred to as ***synchrotron radiation***. When a flare occurs, electric fields arise which accelerate the particles of the plasma. Electrons are accelerated in the opposite direction from protons or positive ions. When these charges interact with the magnetic fields that are present, they accelerate in circular or spiral-shaped paths around the field lines. Electrons, with their small mass, have a high acceleration and produce synchrotron radiation with a wavelength on the order of 10 cm.

The level of 10.7-cm emission seems to parallel the level of solar activity. In fact, radio emissions follow the 11-year sunspot cycle, reaching maximum intensity during times of sunspot maxima (Figure 3–11). It is hoped that the 10.7-cm radio emission will provide another clue that will help us forecast flares.

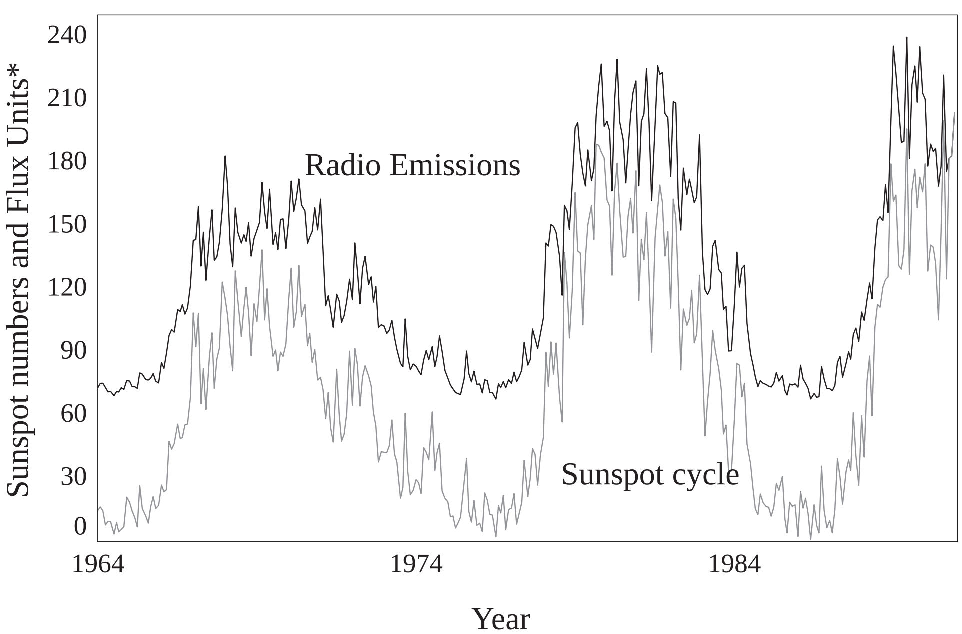

Figure 3–11.*—Radio emission (10.7 cm flux) follows the sunspot cycles fairly well.*

** Flux Units are 10^{-22} W / (m^2 Hz)*

Problems and Questions

1. Compare the angular size of the sun and moon as seen from the earth. Why is this significant during solar eclipses? How does this relate to the red color of the chromosphere?
2. In what parts of the Sun are each of the following radiations produced? Describe the processes that produce each radiation. (a) white light. (b) red light with a wavelength of 656 nm. (c) ultraviolet (d) x-rays (e) radio waves (f) 10.7 cm microwaves.
3. What is the ***Zeemann effect*** and how does it help us study the Sun?
4. Compare the appearance of the Sun in white light to its appearance in the $H\alpha$. What advantages does each have? What features of the Sun can be seen in x-rays but not the white or $H\alpha$?
5. Find the the energy level difference (in ev) in the hydrogen atom that produces the $H\alpha$ line.
6. Describe the 22-year solar magnetic cycle. How is it related to the sunspot cycle?
7. What is the "butterfly" pattern and what does it tell us about the formation of sunspots?
8. What are Fraunhofer lines, what causes them, and what do they tell us about the Sun?
9. What are filaments and neutral lines? How are they related to each other?
10. How was Skylab significant in our understanding of the Sun?
11. What is coronium? Can it be found today?
12. Estimate the orbit size (radius) for the GOES–7 satellite, given the fact that the orbit is geosynchronous. Give your answer in meters and in Earth radii ($R_e = 6.38 \times 10^6$ m). Hint: this is an estimate that Isaac Newton was capable of in 1660.
13. Why is black body radiation called black?