The Sun and How to Observe It

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Jamey L. Jenkins

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My gratitude goes out to Amber Eldridge for information regarding skin protection and the Sun, and also to Ray Cash and Robert Hess, who provided outlines of their dedicated solar telescopes. And to all my correspondents on the Internet who share this wonderful hobby with the world and me.

Mostly, though, I offer my deepest appreciation to my wife, Mary, and my immediate family for permitting me the time out of our busy lives to attempt to put on paper an encouraging word or two that inspires what should be a thrilling experience for anyone possessing the desire to observe the Sun. Observing most astronomical objects and particularly the Sun requires unending patience, continual development of your astronomical eye, and the quenching of a relentless thirst for knowledge. The Sun with its multi-faceted face tests and satisfies these essentials.

Clear Skies
Jamey Jenkins IL, USA

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About the Author

Jamey Jenkins has been a regular contributor to the Sunspot Program of the American Association of Variable Star Observers (AAVSO) since 1990 and an active observer for the Association of Lunar and Planetary Observers (ALPO) Solar Section since 1998. He has been Assistant Section Coordinator of that group for the last 3 years. An astronomy enthusiast since youth, he also has published numerous articles in *The Strolling Astronomer* and images in *Sky & Telescope*.

Living among the corn and soybean fields of mid-America affords wide-open views of the night and daytime sky. When not exploring the Moon, planets, or his favorite celestial body, the Sun, he earns a living as a digital pre-press specialist with R. R. Donnelley, the largest commercial printer in North America at its Crawfordsville, Indiana, facility.

Jamey and wife Mary are the parents of four adult daughters and four grandchildren. “We are a family of varied interests and talents. We are printers, health care professionals, musicians, teachers, historians, social service providers, and computer technology specialists. Astronomy, though, has touched only two of us. My son-in-law Chris and I are followers of Galileo and Copernicus, spending our spare time enjoying the beauty of the heavens and sharing it with anyone that is curious enough to peek through the telescope,” says Jamey.

Introduction

Over four decades ago an amateur astronomer browsing the stacks at his or her local library might have come across a copy of William Baxter's book, *The Sun and the Amateur Astronomer*. This English author's text gave aspiring solar astronomy buffs a look into the how and why of techniques used for observing the Sun. Baxter carefully painted a picture of how an amateur astronomer, using only a modest telescope, sketch pad, and sheet film camera, could leisurely record solar activity. Over the years a number of devotees, including myself, found Baxter's work invaluable in the pursuit of their solar astronomy hobby, his being the first book of its kind written for amateur studies of the Sun.

An amateur observer from that era would hardly be able to imagine the current astronomy scene. Observational astronomy has experienced a complete revolution! For the most part pencil and paper, vital in Baxter's time, are now relegated to note taking. The electronic sensor has replaced film, and advanced video techniques offer the most promise for those attempting to record the finest solar detail in their photographs.

Another surprise for the earlier observer might be the availability of commercial telescopes dedicated specifically to solar observations. In the past monochromatic observing, done by utilizing a thin slice of light from the solar spectrum, was available only to the craftsman capable of building the complex, delicate instruments needed to perform such observations. These instruments, the spectrohelioscope and monochromator, were expensive and often beyond the skill of the typical telescope maker to construct. Since that time, the availability of solar telescopes and filters for Hydrogen-alpha and Calcium-K observing have awakened an interest in daytime astronomy to a whole new generation of observers. Using an off-the-shelf solar telescope, today's amateur astronomers coupled with an inexpensive computer webcam are producing time-lapse movies of chromospheric activity that was previously only the domain of a professional astronomer located at a high-altitude solar observatory. Never before have such opportunities existed for amateur observers. This is truly an exciting time to be a solar astronomy hobbyist.

With this book we hope to project the sense of excitement that so many observers experience when we point our telescopes sunward. If you are new to solar astronomy, you should become educated on how to safely explore the Sun. Veteran observers could find in these pages a new twist to an old technique that allows seeing the Sun in a different way.

As a variation on the hobby of star gazing, solar observing provides an alternative to late nights, cold fingers, and fumbling in the dark trying to locate that expensive eyepiece you've just dropped in the dew-soaked grass. All events happening on the Sun are unique and never will be repeated exactly. This is much of what attracts individuals to solar astronomy and is the reason there is a scientific value to each of your observations. Whether you follow the growth and decay of a sunspot group, the rapid emergence of a solar flare, or the spray of an erupting prominence at the Sun's limb, one fact is certain: the Sun will always present a uniquely different face, each and every day.

In order to appreciate the Sun and its ever-changing face, it's valuable to have an understanding of what it is, how it works, and how it relates to our world. The Sun *is* a star, a sphere of glowing hot gases, one star in a massive collection called the Milky Way galaxy. Enormous pressures exist inside the Sun, creating an environment unlike anything we could possibly experience on Earth. Nuclear forces that influence conditions on our Earth and the other planets in the Solar System are released deep within the Sun's core. The first part of this book will give an overview of these topics. We will begin by looking at the differences and similarities between the Sun and other stars, how the Sun was born, and how energy makes its way from the Sun's core to our backyards. Once that basic foundation is established, the discussion will shift to how an amateur astronomer of the twenty-first century observes the Sun. Together, we will explore the cavalcade of features to be seen in white and monochromatic light and the instruments that can be used to safely observe them. In the latter part of the book, we will review modern techniques for rendering and sharing your solar observations with the world, itself a hobby within a hobby.

A word of CAUTION to prevent the uninitiated from rushing out into the daylight and directing their telescopes skyward. Solar observing can be a very dangerous activity unless certain safety guidelines are followed, a theme you will find repeated throughout this book. The Sun emits huge quantities of heat, light, and radiation, which the solar observer must respect at all times. The atmosphere and magnetic field of Earth fortunately act as a shield for much of the radiation; the daily danger to the Earth-bound astronomer is in the brightness and the infrared and ultraviolet light of the Sun. These invisible wavelengths must be filtered out, and the intensity of the illumination reduced to an acceptable level for safe visual studies to be conducted. **Without these necessary precautions, blindness of the observer will result.** Of course, this topic will be discussed in greater detail in the following chapters. Regardless, the author and publisher cannot be held responsible for the careless actions of any solar observer disregarding safety procedures. The rule of thumb regarding solar observing is this: Always err on the side of safety when observing the Sun. Do that, and you'll be able to enjoy many years of watching one of nature's most magnificent spectacles from your own backyard.

Chapter 1

The Sun, Yesterday and Today

One of Millions

As a young man I often took a nightly stroll down a pathway that led to a meadow far from my home. Looking skyward on many of those dark summer nights I studied a heaven full of silent, twinkling stars that on occasion reminded me of a smattering of jewels flung across a dark velvet cloth. I would see a pale diffuse web of light rising in the northeast near Cassiopeia that stretched clear to the southern horizon. Exploring this diffuse web with a small pair of binoculars revealed to me that it was composed of a countless number of individual stars. But to the naked eye this pale light was deemed to be the arm of a spiral galaxy, snaking its way to a hub located in Sagittarius. In fact, every naked-eye star I could see from that country pathway was part of this galaxy's family. The evening sky seemed to be saying, "Welcome to the Milky Way."

The Milky Way is the galaxy where we live, orbiting on a sphere shaped platform we call Earth, about a typical star that long ago our ancestors chose to call Sol, or the Sun. There was a time, only several hundred years ago, when people thought Earth was the center of the universe and that all celestial bodies were revolving around it. And why not? Isn't that how it appears to the untrained eye? Today, we know the truth. Earth is one of many thousands, if not millions of bodies, large and small that circles the Sun. Furthermore, this assemblage of gas, liquid, dust, ice, and rock we call our Solar System orbits the galactic nucleus, the hub of the Milky Way.

Careful observations by astronomers tell us that the Sun is located about one-third of the way from the outer edge of the Milky Way, a distance of about 25,000 light-years from the center of the galaxy. One light-year measures 9.46×10^{12} km. Our galaxy has an overall diameter in the vicinity of 80,000 light-years. Since the Solar System travels at nearly 230 km/s through space, it takes the Sun close to 200 million years to complete a circuit of the galaxy. Scientists say that the Milky Way contains hundreds of millions of other stars besides the Sun, some similar but many different (Figure 1.1). Our view of an Earth-centered universe has changed dramatically in the last 500 years!

What Exactly is the Sun?

The Sun is a typical star, a giant sphere-shaped ball of gas that through nuclear reactions releases energy in its core. Due to the great distances found between stars, most appear similar when viewed through a telescope. In reality, though,

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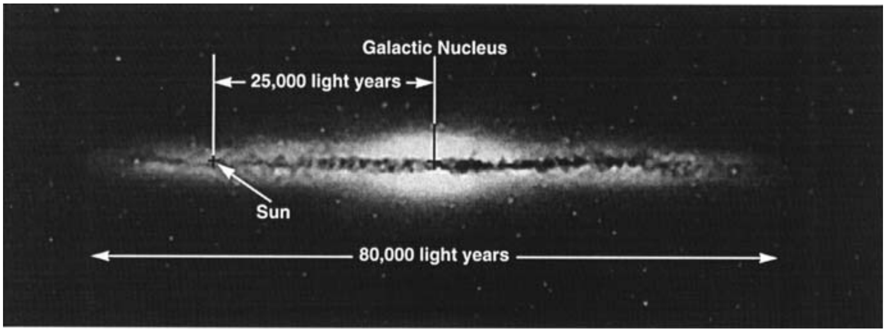

Figure 1.1. The Sun is one of millions of stars within the Milky Way Galaxy. In this artist's rendition, the Sun is situated about 25,000 light years from the center of the galaxy.

stars have a wide range of individual characteristics. All stars including the Sun vary from one another in color, temperature, and brightness, not to mention mass, composition, and age.

Although the Sun is 1.3 million kilometers in diameter and provides a reasonable angular size against our sky, on average 32 arc minutes, stars are almost always seen as virtual points of light. This is true regardless of the fact that some stars are absolute giants when compared to our Sun. Take the star Antares in the constellation Scorpius. Antares is a red supergiant about 520 light-years distant from our Solar System and about 230 times larger in diameter than the Sun. In spite of its gigantic size, Antares is still seen as a point through our telescopes.

The distance separating the Sun from Earth is, on average, 150 million kilometers. Remember, we are actually closer to the Sun during the month of December and farther away in June, an indication that Earth's orbit is not circular but elliptical. Compare the Sun's distance from us to the next nearest known star Proxima Centauri, at a distance of 4.2 light-years or to Sirius, the brightest star in the night sky, at 8.6 light-years. One analogy that puts such astronomical distances as these in perspective is this: "Visualize the Earth-Sun system with Earth represented by the tiniest of pebbles and the Sun as a large marble, separated by a distance of only 1 m. Now, with this scenario, the nearest star Proxima Centauri would be over 265 km away!" As you can see, the Sun is unique because of our nearness to it and its great distance from the other stars.

Another significant difference between the Sun and stars is brightness. The system called magnitude defines the brightness of a celestial object. On the magnitude scale, objects assigned larger numbers are fainter; those with smaller numbers appear brighter. Each step of magnitude is designed to be about 2.512 times brighter or fainter than the preceding step. In other words, stars of 2nd magnitude look about one hundred times brighter than stars of 7th magnitude ($1 \times 2.512 \times 2.512 \times 2.512 \times 2.512 \times 2.512$).

There are two basic kinds of magnitude, absolute and apparent. Absolute magnitude is a measurement of the light received from an object when placed at a set distance of 32.6 light-years from Earth. Absolute magnitude describes a body's true brightness. Apparent magnitude measures the amount of light we see regardless of an object's distance from Earth. This is ordinarily the magnitude assigned to an object; it measures how bright a celestial body appears to us. The brightest object in our sky, with an apparent magnitude of −26.8, is the Sun. The Moon at full has a magnitude of −12.7, Sirius shines at −1.4, and Polaris, the North Star, is magnitude +2.1.

Generally, stars of about 6th magnitude are as faint as can be glimpsed by an observer without optical aid. The dimmest objects found during the Hubble telescope's Ultra Deep Field Survey are on the order of 31st magnitude; some stars can appear very faint indeed.

Because a star's color is directly related to its surface temperature, and stars vary from relatively cool to very hot, a virtual rainbow of starlight is visible in the night sky. This relationship between temperature and color, called, Wien's Law, states that in principle the dominant emission wavelength of a blackbody (wavelength of its color) multiplied by its temperature must equal a specific numerical factor. Blackbodies are objects that reflect no light, but do absorb and re-emit radiation. Stars are blackbodies. The peak output in a star's spectrum determines its dominant emission wavelength; it is this wavelength or position in its spectrum that produces the star's color, and serves as a factor, according to Wien's Law, in its surface temperature. This makes sense if you consider a fireplace poker left in a fire. The poker becomes a glowing red color (called red-hot), because of the specific temperature it has attained. Stars with a specific temperature glow a particular color.

Table 1.1. Pertinent facts regarding the physical makeup of the Sun. Data courtesy of NASA

Diameter: 1,391,980 km (109 Earth diameters)		
Mass: $1{,}989{,}100 \times 10^{24}$ kg (333,000 Earths)		
Volume: $1{,}412{,}000 \times 10^{12}$ km^3 (1,304,000 Earths)		
Visual magnitude: −26.74		
Absolute magnitude: +4.83		
Spectral type: G2V		
Distance from Earth:	Minimum	147,100,000 km
	Mean	149,600,000 km
	Maximum	152,100,000 km
Apparent diameter:	Minimum	31.4 min of arc
	At 1 A.U.	31.9 min of arc
	Maximum	32.5 min of arc
Central pressure: 2.477×10^{11} bar		
Central temperature: 1.571×10^{7} K		
Central density: 1.622×10^{5} kg/m^3		
Central composition: 35% H, 63% He, 2% C, N, O. . .		
Photosphere pressure (top): 0.868 mb		
Photosphere temperature (top): 4400 K		
Photosphere effective temperature: 5778 K		
Photosphere temperature (bottom): 6600 K		
Photosphere composition: 70% H, 28% He, 2% C, N, O. . .		
Sidereal rotation period: 25.38 days		
Synodic rotation period: 27.27 days		
Age: 4.57×10^{9} years		

The color of the Sun is yellow-white, similar to that of the star Altair, in the constellation of Aquila. Contrast that with the blue of Bellatrix in Orion the Hunter or the orange of Aldebaran in Taurus the Bull. Stars with a blue hue, such as Bellatrix, have surface temperatures of 20,000–35,000 K (water boils at about 373 K). Aldebaran's cooler surface temperature is approximately 4000 K. Our Sun checks in at about 5800 K.

The Sun, without a doubt, is the king of our Solar System. We are dependent on its existence to provide warmth, light, and inevitably life to our world. Understand also that the Sun has its place among the stars of the heavens. It is a typical star, and because of our ideal location, we have a front row seat to witness phenomena that would evade us on all other stars in the universe. This vantage point near the Sun helps us to contemplate, and understand, the differences between the Sun and the other stars (Table 1.1).

The Origin of the Sun

The Sun and its Solar System, we believe, began as a vast cloud of gas and dust called the solar nebula. It is speculated that the nebula had a mass of two or three times that of the Sun and a diameter of at least one hundred times the Earth to Sun distance. This cloud was composed of a number of elements including hydrogen, helium, carbon, nitrogen, oxygen, neon, magnesium, silicon, sulfur, and iron. Present but not in abundance were nickel, calcium, argon, aluminum, and sodium. Several other elements in only trace amounts were also to be found, including gold.

Since the beginning, which we call the Big Bang, hydrogen and helium always have been the most prolific elements of the universe, totaling almost 98% of its combined mass. The other elements of the solar nebula were produced inside the first stars, through nuclear processes or by experiencing the destructively powerful ending to a star, called a supernova.

Dust particles, found within the solar nebula, were likely coated with an "ice" created by some elements that were condensing in the frigid temperatures of that time. Tugging on these dusty ice particles, gravity would cause a general tendency of their movement toward the center of the solar nebula. In time, as these particles collected, gravity-induced density and pressure would increase in the central region of the solar nebula. Inside this so-called protosun it became crowded; little room existed between atoms, causing them to repel one another, producing thermal energy, or heat. This process, the turning of gravity's energy to heat, is called the Helmholtz contraction. To prevent all matter from being drawn into the center by gravity, with no planets forming, angular momentum or a rotation of the solar nebula had to somehow be present. Rotation of the nebula may have been a natural characteristic, or it could have been the result of a passing shockwave from a nearby supernova explosion.

Eventually, the pressure and temperature resulting from the contracting gas and particles inside the solar nebula would have reached a point where the new protosun could "switch on" and begin to glow.

Although gravity was responsible for initiating the early Sun, the process of Helmholtz contraction was not one that could sustain a star's appetite for energy. A different process had to be at work, fueling the Sun as we see it today. What was it? The answer to that question came in 1905 from Einstein's theory of relativity, which states that energy and mass are interchangeable. The equation, $E = mc^2$, tells us that energy (E) is equivalent to an object's mass (m) times the speed of light (c) squared. What does this mean to us in our understanding of how the Sun is powered? Simply said, a tiny amount of matter can be converted to a stupendous amount of energy! Physicists after a time proposed that given the right conditions of temperature and pressure, as are found in the Sun, hydrogen atoms could fuse together, forming helium, with a portion of the Sun's mass being released as energy, fueling the solar furnace. This is just what the Sun does.

How the Sun Works

All stars, including the Sun, are energized by nuclear reactions deep within their core. The pressure and temperature in the Sun's core is so extraordinary high that four hydrogen protons fuse to become a single helium nucleus. It's estimated that the pressure in the core is nearly 340 billion times the air pressure at sea level on Earth. Because of such intense pressure, temperature in the core of the Sun exceeds 15 million Kelvins.

Gas within the core has a density many times that of lead, and conditions are so extreme that electrons are stripped from their atoms. This process of separation of electrons from an atom is called ionization; an atom with one or more electrons missing is called an ion. Atoms within the core of the Sun are totally ionized, and in this state a gas is called a plasma, which is a brew of ions and electrons that react energetically with magnetic fields. Stars having a mass equal to or less than the Sun go through a process of converting hydrogen to helium; this process is referred to as the proton-proton cycle. Stars with a greater mass than the Sun also convert hydrogen to helium, but through a different process called the CNO cycle.

The proton-proton cycle results in the regeneration of millions of tons of hydrogen to helium in the Sun every second. As time goes by, the Sun will become lighter and exhaust the hydrogen it has been burning for billions of years. One day, after the hydrogen is gone, the outer layers of the Sun will be blown away to form what is ironically called a planetary nebula. Sadly, our planet will cease to exist, and in the end, the Sun will remain an insignificant white dwarf star. No need for immediate concern, however; there is an estimated 5 billion additional years of hydrogen available. The hydrogen to helium fusion process has already been underway for nearly 4.6 billion years (Figure 1.2).

Energy from the Inside Out

Thermonuclear fusion within the Sun's core is the source of solar power. Tremendous amounts of energy are being released, yet the Sun does not explode like an atomic bomb. Because of the forces of equilibrium, the Sun remains in a relatively steady state. Outward pressure from the compression of gas prevents gravity from causing the outer layers of the Sun to collapse into the core. This balancing act of pressures is called hydrostatic equilibrium. Likewise, the nonstop conversion of hydrogen to helium is happening at a uniform rate. There is no sputtering, starting, or stopping of the hydrogen burning. This continuous fuel-in, energy-out rate is called thermal equilibrium. Without these two balancing principles, the Sun as we know it couldn't exist.

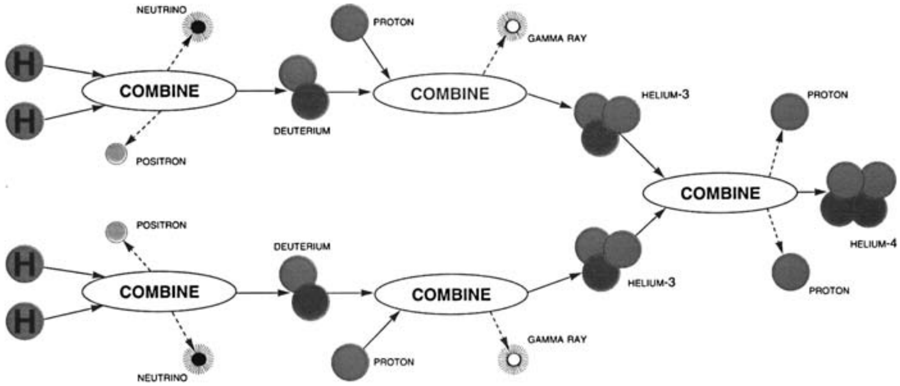

Figure 1.2. Energy is created within the core of the Sun through a process called the proton-proton cycle. In this chain-reaction, two hydrogen protons combine to form deuterium, an isotope of hydrogen. During the first phase of the conversion process, one of the protons becomes a neutron, resulting in its casting off a neutrino and a positron. Next, the deuterium nucleus combines with another proton. This second reaction results in energy being released as a gamma-ray photon. The new $helium_3$ nucleus then combines with another $helium_3$ nucleus to produce a $helium_4$ nucleus, and two protons are released as a result.

But how does the energy get from the solar furnace in the core to the region we call the photosphere and beyond? To begin, we must recognize that the Sun is a body consisting of a number of zones or layers. Imagine for a moment the cross-section of a baseball. At the center of a baseball is a smaller hard rubber core, which is wound with a string like material, woven tightly to build up the height of the ball to its proper circumference. Around this again is stitched the outside covering of the ball. A baseball is constructed in layers, and so is the Sun. From the solar interior to the exterior, we find the core, then the radiative and the convection zones. Immediately above the convection zone we find the photosphere, the first layer of the solar atmosphere. The light we see from the Sun emanates from the photosphere.

Radiative Zone

Progressing outward, directly above the core and extending to a point that is nearly 70% of the way from the center to the solar radius is the radiative zone. Near the bottom of this layer the temperature is about 8,000,000 K, and the density several times that of lead. Gamma ray photons are a form of energy released in the Sun's core during nuclear fusion. Photons are light rays. As the photons flow from the core into the radiative zone, the gases present there will absorb and re-radiate the rays. The general tendency of photons is to depart from the hot interior toward the cooler photosphere. Inside the Sun, however, it is very crowded. The high-energy gamma ray photons are knocked from side to side, absorbed, re-emitted, and sometimes take a path back toward the center, spending a hundred thousand or more years finding their way through this zone.

Convection Zone

Above the radiative zone and below the photosphere, having a depth of about 210,000 km, is a layer termed the convection zone. Here, energy is transported through the passage of plasma from deep in the zone to the upper layer, the photosphere. As the hot gases rise, they cool and fall back toward the Sun's interior in a process known as convection. The analogy of a bubbling pot of oatmeal often comes to mind when describing solar convection. Heat, generated at the bottom of a pot, collects in pockets within the oatmeal. A heated pocket then begins to rise to the surface of the oatmeal, transferring energy and producing a "bubbling" in the pot. On the photosphere a similar effect can be seen. The photons produced in the core and passed through the radiative zone create convection cells, causing them to rise to the solar surface. On the Sun, each 1000-km-diameter convection cell, called a granule, makes its way to the top of the convection zone at nearly 1500 km/h. Releasing energy in the photosphere, the granule cools as the gas flows back to the solar interior along the granule's outer wall. These darker, cool outer walls give granules their unique kernel shape.

Granules cover the entire visible surface of the Sun, totaling several million at any given time. The life of a granule is "brilliant" but short, each lasting perhaps 5–10 min, only to be replaced by the next bubble emerging from deep in the convection zone (Figure 1.3).

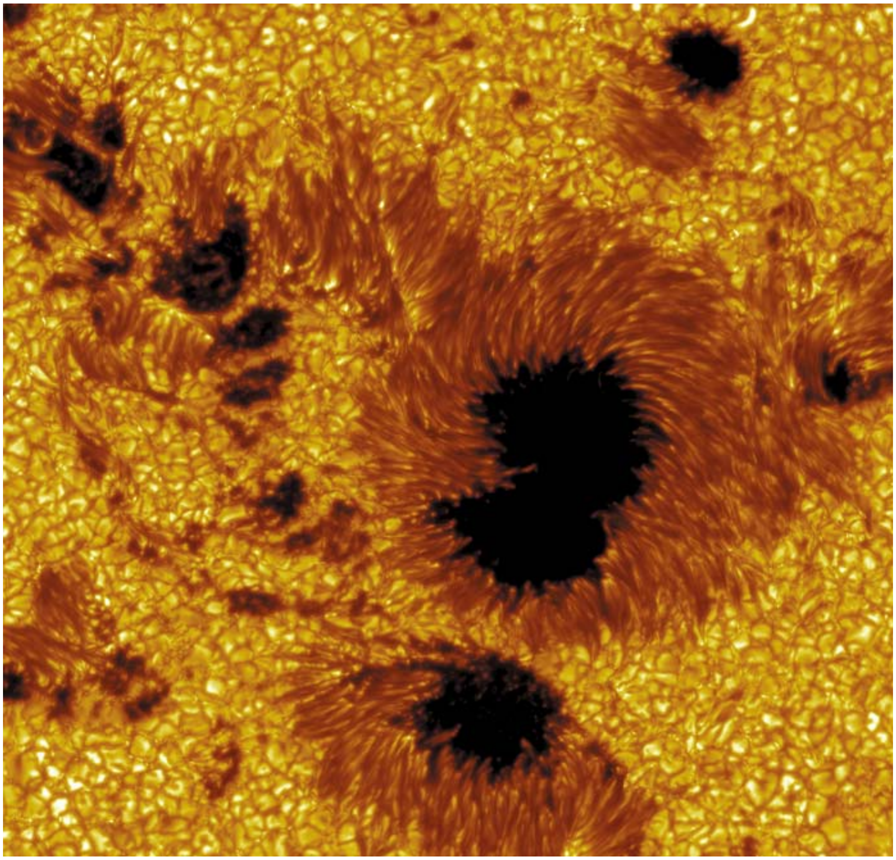

Figure 1.3. High-resolution image of a sunspot group with granules surrounding it. Obtained with the 1-m solar telescope at La Palma, Spain. Courtesy of Royal Swedish Academy of Sciences.

There is another movement of plasma in the convection zone that has been shown to occur from the equatorial region of the Sun to the polar areas. This movement is called the meridional flow and may be responsible for the migration of sunspot groups toward the equator as a solar cycle progresses. The solar cycle is roughly an 11-year-long cyclic period of activity on the Sun. As time advances, indicators of an active Sun, such as sunspots and flares, increase in quantity, until a peak occurs and then activity begins to decline. Gradual movement of plasma due to the meridional flow creates a circuit or loop, traveling from the solar equator to a point near the Sun's poles. In the polar regions, the plasma makes a curl under toward the bottom of the convection zone before resuming a slower return trip to the equator.

Sunspot migration from the higher solar latitudes to the equator is tied to the belief that groups are magnetically anchored to the lower region of the convection zone. The slow pace of the meridional flow is conjectured to be a factor for sunspots surfacing closer to the equatorial regions as a solar cycle advances.

Photosphere

The photosphere (sphere of light) is the beginning of the solar atmosphere and the lowest level we can see visually into the Sun. Below this layer, gas is so opaque that it is impossible to see through. However, in the photosphere watchful eyes see granulation, sunspots, and near the solar limbs, wispy material called faculae. Activity in the photosphere follows the 11-year ebb and flow of the solar cycle.

The photosphere is akin to the covering on the baseball referred to earlier. When the surface of the Sun is spoken of, this is the layer meant. Of course, the Sun really has no "surface," being gas, but because this region is the emitter of most of the light we see, it appears to be the surface. Approximately 500-kilometers thick, the temperature at the lower boundary is about 6600 K, while at the top it has dropped to nearly 4400 K, with a pressure less than 1 mb.

Photons from the inner zones reaching the photosphere are set free and shoot into space. Streaming out of the Sun, they make it a brilliant and dangerous object to watch without sufficient eye protection. It's marvelous to contemplate that the light we see leaving the Sun today started its course from the core and through the several outer layers many thousands of years ago (Figure 1.4).

Magnetic Fields

Below the Sun's surface, atomic forces from the pressure of gas prevail, but in the photosphere and beyond magnetism takes over as the dominant force. The Sun's magnetic field is the result of rotation and convective motions within the solar interior. Helioseismologists, astronomers who study low-frequency sound waves originating in the Sun, tell us that the radiative zone and core rotate like that of a solid body, with a period of about 27 days. Rotating differentially, the convection zone and upper layers experience a rotation rate near the equator of about 25 days; near the polar regions, acting as if the it were made of liquid, the Sun's rotation rate is about 36 days.

Last century, astronomer Horace Babcock created a theory that helped explain the appearance of sunspots within the photosphere. According to Babcock, the

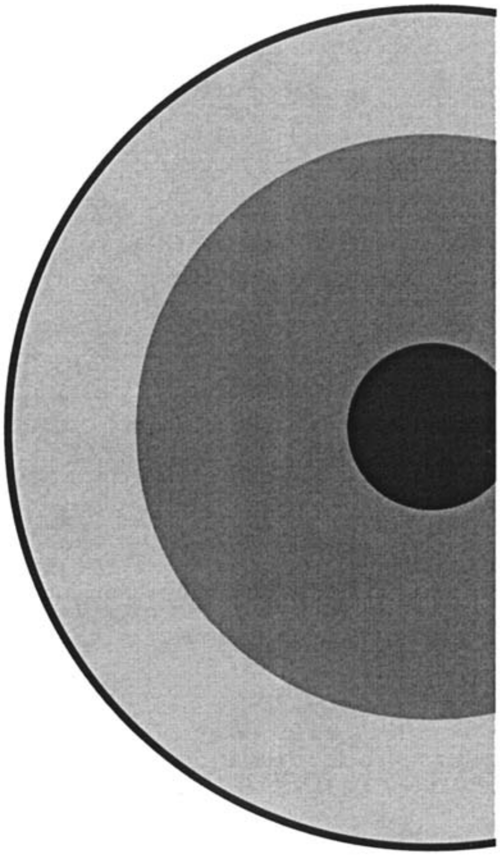

Figure 1.4. Internal layers of the Sun.

magnetic field of the Sun is influenced by plasma flow inside the solar interior. Shearing between the solid acting radiative zone and the fluid-like convection zone also contributes to the magnetic field. This region between the two zones is called the tachocline.

The nature of a plasma as it moves is to create a magnetic field. The lines of the Sun's magnetic field run parallel to the axis of rotation, from pole to pole in a north-south direction. Differential rotation in the convection zone wraps the magnetic field round and round the Sun, similar to how the baseball model is wrapped with string about its core. This stretching or wrapping occurs because the magnetic lines are being dragged along with the charged particles of plasma.

Convection is also at work transferring energy from the radiative zone to the photosphere, with a vertical boiling motion. This vertical movement of plasma causes a tangling of the field lines. The tangled field lines create an increase in strength while developing kinks in their paths. A strand or kink of magnetic field suspended in the convection zone is called a flux tube. Smaller flux tubes pop through the solar surface at bright points known as filigree, which have a diameter around 150 km. Much larger flux tubes are dark and give birth to pores and sunspots.

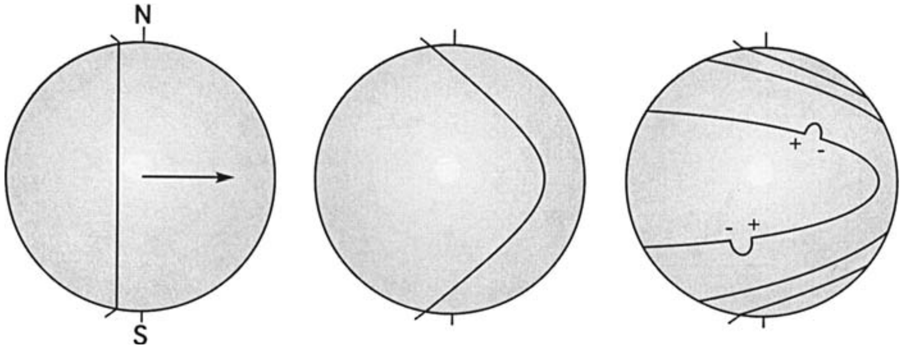

Figure 1.5. Sunspot theory says that a magnetic field line runs from north to south on the Sun, as at the left. The differential rotation of the Sun illustrated in the center causes the magnetic field to stretch and wrap around the Sun. In the right diagram, after many rotations the magnetic field has become tangled with other field lines; strengthening, it rises to the photosphere to form an active region.

When a tube has reached strength sufficient to cause it to rise to the surface and burst through, leaving a magnetic impression on the photosphere, the tube is called an active region. Like the horseshoe magnet has a north and south pole, so does an active region. The magnetic field projects above the photosphere and arches from one polarity (+) to the other (−). The leading and following magnetic polarities of all active regions are identical, depending on which hemisphere contains the region; the polarities are reversed in the opposite hemisphere. In a process not fully understood, these fields switch polarities in step with the 11-year cycle of sunspot activity. Two complete solar cycles, therefore, make one magnetic cycle, a period of about 22 years.

Sunspots, with their dark umbral and lighter penumbral regions, appear within magnetic fields on the photosphere because convection is stifled. Only smaller amounts of energy via convection are able to reach an active region, which becomes cooler than its surroundings and appears darker, producing a "blemish" on the surface. Although some spots appear very dark, this is a false impression, because even the darkest sunspot, if seen alone in the sky, would still be about as bright as the full Moon (Figure 1.5).

Directly above the photosphere is the chromosphere, and beyond that the corona. These two features are easily visible during a total solar eclipse, the chromosphere as a reddish-pink ring hugging the limb of the Sun at totality and the corona as the ghostly white solar atmosphere extending several radii beyond the eclipsed Sun. Nearly all the activity on the photosphere, in the chromosphere, and in the corona is related to the Sun's magnetic field.

Chromosphere and Corona

Beyond the photosphere is a layer called the chromosphere (*chromos* means "color"). With a thickness of about 2000 km, the temperature in the chromosphere is typically 10,000 K. The gas of the chromosphere is rarefied, or less dense than below, making it difficult to see because of the overwhelming intensity of the photosphere. The chromosphere is reddish-pink because of its emission strength at 656.3 μm, which is the wavelength of the Hydrogen-alpha line in the solar spectrum. By utilizing special instruments that pass only certain wavelengths of light, astronomers are able to study features within the chromosphere.

Activity in the chromosphere takes a variety of forms. One large-scale feature is the chromospheric network. This is a net-like pattern that overlays the super-granulation pattern visible in the photosphere. The network is made of small patch-like areas only a few arc seconds across. The patchwork appears bright when viewed in the light of Calcium. If the network is viewed in Hydrogen-alpha light, dark protrusions called mottles are revealed. When the mottles are longer than a couple seconds of arc, they are known as fibrils.

Spicules are easily seen at the limb as an emission (bright) feature appearing like tiny jets of gas flaming out of the Sun. On the disc they appear dark, taking several forms, such as "brushes" or "chains." Spicules rise to an average height of 7500 km and a width of about 800 km.

Since hot gas is ionized, it clings to the strong magnetic fields of the Sun, tracing out lines and loops where they exist. This allows us to see the shape of a magnetic field, especially when it is silhouetted against the darker background sky at the solar limb.

Prominences are clouds or stream-like projections of gas visible above the solar limb. Seen against the disc of the Sun, prominences appear dark and are called filaments. Although prominences come in a variety of shapes and sizes, they tend to fall within two basic classifications, active or quiescent. Active prominences have shorter lives and sub-class names such as surge, spray, jet, or loop. These are energetic events that sometimes end with the prominence being ejected into the corona or beyond. Quiescent prominences last longer, appearing at times on the limb of the Sun as a mound or hill. They are static and slow to change appearance. Prominences are suspended above the photosphere by magnetic fields. Physically, they can be a few thousand to several hundred thousand kilometers in length, ten thousand or more kilometers in width and height, and around 10,000 K in temperature.

Another chromospheric curiosity is the solar flare. It is believed that flares result from released stress within the magnetic field of a sunspot group. Flares sometimes appear as a sudden brightening of an existing plage (bright patchy region within the chromosphere). The initial phase of brightening can be rather quick, from a few minutes to an hour. A gradual decline in intensity of the flare is experienced following peak brightness. The energy output of a flare can be truly astronomical. It would not be unusual for a large flare to produce the equivalent of several seconds' worth of the Sun's total output. Pack all this in an area less than one hundredth of a percent of the surface area of the Sun, and the outcome is spectacular.

Solar flares are known to eject particles of matter from the Sun in addition to deadly radiation. Within a matter of hours to days these particles can reach Earth, disrupting communications, power grids, or damaging spacecraft. This is why it is important for scientists to track solar flare activity around the clock.

Occasionally, an event called a coronal mass ejection, or CME, takes place. The coronal mass ejection is an expulsion of a part of the corona and particles into interplanetary space. CMEs can represent the loss of several billion tons of matter from the Sun. These particles can move at velocities near 400 km/s. Solar flares appear to trigger some CMEs; other CMEs occur without an accompanying flare. The ejected particles are carried by the solar wind to our vicinity in space, causing havoc and initiating beautiful auroras in the polar regions of our planet.

Extending further out from the chromosphere, the gas becomes particularly tenuous. There is a thin region between the chromosphere and corona called the transition zone. From this point outward the temperature begins to increase markedly. Within the corona, to a distance of several million kilometers from the photosphere, temperatures exceed 500,000 K and at times may be more than 2,000,000 K. The heating mechanism of the corona is unknown and remains one of the big questions for solar astronomers to answer.

The light of the corona (meaning "crown") compared to the photosphere is extremely weak and can only be seen during a total eclipse of the Sun or by using a special instrument called a coronagraph, which creates an artificial eclipse. Spacecraft that get above Earth's atmosphere have a particular advantage in studying the corona. Scattered light from dust, refraction, and water vapor in the atmosphere hamper the Earth-bound observer, but in space these conditions do not exist, favoring observation of the Sun's corona.

The shape of the corona varies with the strength of the sunspot cycle. During sunspot minimum the corona is seen more fully and is extended around the solar disc. At sunspot maximum the corona is restricted to the equatorial or sunspot zones. This restriction is attributed to an increase in magnetic activity during the solar cycle.

As the corona reaches further from the Sun, it eventually becomes one with the streams of charged particles escaping the Sun, called the solar wind. Comets are excellent proof of the solar wind's existence. As a comet approaches the inner Solar System material in it is stirred up and gassed out by the heat experienced as it nears the Sun; the solar wind then pushes this material away, forming the comet's tail.

Energy begins as hydrogen in the Sun's core, and through the proton-proton cycle this energy becomes photons and particles slowly making their way through the solar interior to the photosphere, where they are released, giving us warmth, light, and life. In a way, we are residents of the Sun, living in its stream of constant emissions. Having such a close relationship with a natural occurring power plant, we are much the wiser to strive for a full understanding of how the Sun affects Earth, and ourselves.

The Earth-Sun Relationship

Within the last decade or two a new term, space weather, has come into vogue to describe the environment of space near Earth, as it has been affected by the release of energy and particles from the Sun. The study of space weather is critical in understanding Earth's environment.

Earth, with its iron core, behaves as though it were a huge magnet, having north and south poles due to the dynamo effect. Lines of magnetism emerge from these poles and arch out into space for tens of thousands of kilometers and return to the opposite pole. Although we usually think of magnets as possessing attracting power, repulsion is also a characteristic of magnetism. Objects that have a charge and are moving will be repelled, or pushed away, by a magnetic field. The large magnetic field surrounding and protecting Earth is called the magnetosphere.

As discussed earlier, the Sun has a steady output of charged particles and bits of matter that is collectively termed the solar wind. Streaming throughout the Solar System at about 400 km/s the solar wind flattens Earth's magnetosphere on the side facing the Sun. It is as if you were walking against a strong breeze, with an