Solar Physics
and Terrestrial Effects

A Curriculum Guide for Teachers
Grades 7–12

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Acknowledgments

Solar Physics and Terrestrial Effects is the result of a unique collaboration from 1992-1996 between scientists at the Space Weather Prediction Center (SWPC) in Boulder, CO, and two Boulder Valley School district high school physics teachers. The combination of the knowledge and expertise at SWPC with the personal experience of teachers, allowed for the production of this curriculum that will give students a taste of one of the most spectacular and exciting applications of physics.

The interest and enthusiasm of the scientists and staff at SWPC has been an inspiration for us as working school teachers. We would like to thank Ernie Hildner and Barbara Poppe for conceiving this collaboration, and helping to bring it about; and extend many thanks to the scientists who worked with us: S. Ananthakrishan, Patricia Bornmann, Grant Burkhart, Larry Combs, Paul Dusenberry, Dave Evans, Howard Garcia, Gary Heckman, Harold Leinbach, Lorne Matheson, Pat McIntosh, Tad Sargent, Zdenka Smith, Howard Singer, and Ted Speiser. Special thanks go to Anuranjita Tewary, a student intern, who carefully typed and prepared the original draft of this document.

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To the Teacher

Solar Physics and Terrestrial Effects is not a step-by-step guide for teachers that will take away from your already over-crowded curriculum. Rather, it is a resource for you to pick and choose from, so that you may enhance your existing course and provide some state-of-the-art applications of physics.

The guide consists of three main parts: a short textbook, a hands-on activity guide, and resource listings.

- The textbook should provide the necessary background in solar physics for teachers. It could also be used by students, but is written largely at an adult level and therefore may not be easily understood by younger students. Problems for more advanced students are included at the end of each of the four sections and answers to the problems are given at the end of this section.
- The activity section offers ideas for hands-on experiences that can be done in the classroom, using materials that are cheap and easily available. Background information is available in the text for the activities. Any materials that are needed for activities can be obtained from a variety of sources.
- The resources and references section contains a wealth of further possibilities for exploring Solar-Terrestrial Physics, including software, telecommunications, books, and supplies. Students who want to pursue research projects may find this to be especially helpful.

Chapter 1

How the Sun Came to Be: Stellar Evolution

It was not until about 1600 that anyone speculated that the Sun and the stars were the same kind of objects. We now know that the Sun is one of about 100,000,000,000 (10^{11}) stars in our own galaxy, the Milky Way, and that there are probably at least 10^{11} galaxies in the Universe. The Sun seems to be a very average, middle-aged star some 4.5 billion years old with our nearest neighbor star about 4 light-years away. Our own location in the galaxy is toward the outer edge, about 30,000 light-years from the galactic center. The solar system orbits the center of the galaxy with a period of about 200,000,000 years, an amount of time we may think of as a ***Sun-year***. In its life so far, the Sun has made about 22 trips around the galaxy; like a 22-year old human, it is still in the prime of its life.

Section 1.—The Protostar

Current theories hold that about 5 billion years ago the Sun began to form from a huge dark cloud of dust and vapor that included the remnants of earlier stars which had exploded. Under the influence of gravity the cloud began to contract and rotate. The contraction rate near the center was greatest, and gradually a dense central core formed. As the rotation rate increased, due to conservation of angular momentum, the outer parts began to flatten. Some of the dust and vapor near the outer edge of this disk formed smaller condensations, each spinning around its own center in the same direction as the parent cloud. These were destined to become Earth and the other planets of our solar system.

Many stars, at this early stage of their evolution, split into two or three parts, resulting in ***binary star systems*** or multiple star systems. At least two-thirds of the stars we have observed are binary or multiple star systems, but it is not yet known whether stars routinely form planets as our star did. No other planetary systems have yet been observed, due to the great difficulty of seeing dark, small planets at great distances, but it is suspected that large numbers of planets do exist and that conditions suitable for life could be found on these planets. The moon systems of Jupiter and the other giant planets resemble a miniature solar system and thus provide further support for the idea that planetary systems may form rather easily.

The contracting cloud began to heat up, to glow and to exert pressure that counteracted the gravitational in-fall. This glowing core was now a ***protostar***, surrounded by dust and vapor. Had we been able to see it from our present location, the protostar would be quite dark, emitting only a small amount of infrared radiation from its core. The sun stayed in this cocoon-like state for about 10,000,000 years until its true stellar birth. While the protostar slowly radiated its energy away, the pressure in the hot core decreased, allowing the core to continue its collapse. The temperature increased until it became so hot that the first nuclear reactions were ignited.

Section 2.—The Hydrogen Burning Stage

With the start of nuclear reactions in its core, the Sun began its life as a true star, heated not by the meager energy of gravitational collapse but by the nearly inexhaustible supply of nuclear fuel contained in its vast interior. This nuclear furnace has maintained the Sun in a state of near equilibrium, producing just enough heat and pressure to counteract the crushing inward force of gravity and stop the contraction.

The Sun has remained in this stable state for the last 4.5 billion years, but what of its future? The Sun is slowly getting brighter (higher luminosity) and larger, while its rotation rate is slowing. It is believed that the young Sun was only about 70% as bright as it is now; and it had an equatorial rotation period of about 9 days, rather than 27 days as it now has. This higher rotation rate probably caused more eruptive activity on the surface. Overall, the Sun seems to be quieting down in its level of turbulence and eruptive activity; at the same time it is increasing in temperature, luminosity and size. It is predicted that in about 1.5 billion years, when the Sun is 6 billion years old, it will be about

15% brighter than it is at present. By the time the Sun is 10 billion years old, it will be about twice as bright as it now is and have a radius about 40% greater (Figure 1–1).

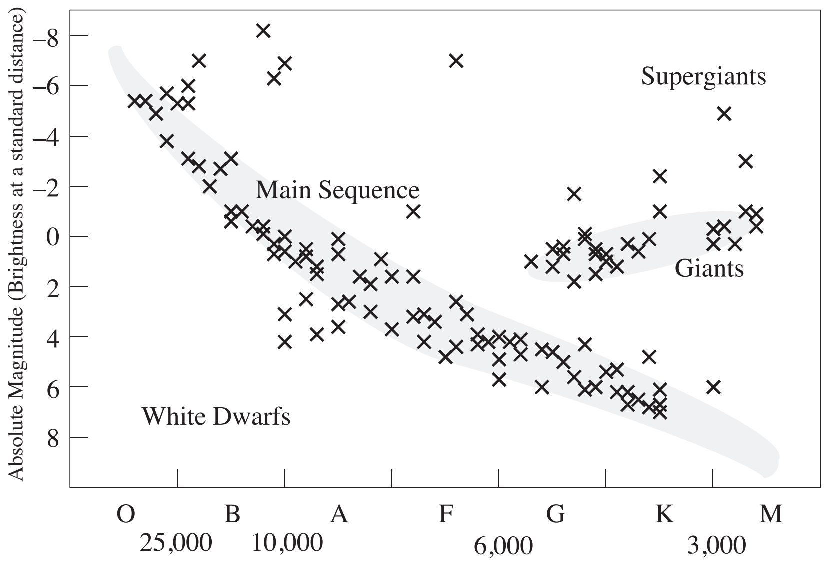


Figure 1–1.—*A Hertzsprung-Russell diagram showing selected stars on a plot of luminosity versus the surface temperature.*

Section 3.—Becoming a Red Giant

During the first phase of a star's life, the nuclear furnace at the core fuses hydrogen nuclei into helium nuclei. After about 10 billion years the hydrogen fuel in the core will be exhausted and the core will begin to contract again (Figure 1–2). This will cause a rise in temperature, and hydrogen fusion will begin in a shell surrounding the core. The surface

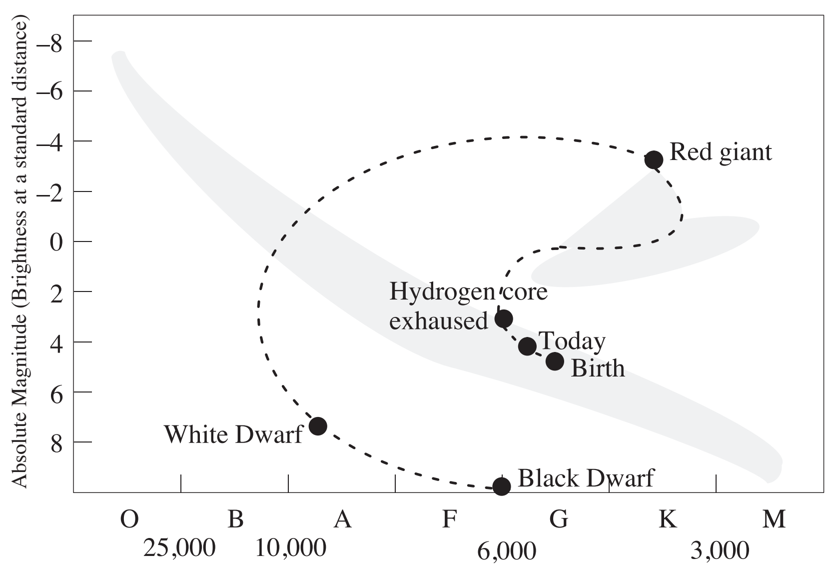


Figure 1–2.—*The life of the Sun on a Hertzsprung-Russell diagram. The Sun was born on the main sequence and has since brightened and cooled. The Sun's hydrogen core will eventually be exhausted, after the Sun is 10 billion years old. The Sun will become, in turn, a red giant, a white dwarf, and a black dwarf.*

layers will expand for the next 1.5 billion years until the Sun is 3 times its present size. An observer on Earth would see the Sun as a bright-red disk, 3 times the size of a full Moon. However, the presence of such an observer is doubtful, for the luminosity will be 3 times greater than it is now, and the Earth will be 100 K hotter than at present.

The Sun will keep expanding in size and luminosity, becoming a ***red giant*** star. Its radius will reach 100 times its present size, so that the planet Mercury will be engulfed and vaporized. Its luminosity will be 500 times the present value, causing Earth's surface to become a sea of molten lava at a temperature of about 1700 K. The Sun will remain in this red giant stage for a mere 250 million years (about 1 Sun-year), while its core contracts and heats up. When the core temperature reaches about 100 million K, the helium ash remaining from the earlier stages of nuclear fusion can begin to fuse into carbon. This will release huge amounts of energy and raise the core temperature to about 300 million K. The ignition of helium fusion is a sudden and explosive event known as the ***helium flash***. As much as one-third of the Sun's mass will be hurled out into space, forming a ***planetary nebula***. The core then will cool to about 100 million K, where it will begin the steady burning of helium. By then it will be about 10 times its present diameter and have 20 times its present luminosity.

Section 4.—Dwarfs, Neutron Stars, Supernovas, and Black Holes

After the supply of helium is converted into carbon, the remaining mass of the Sun will shrink and cool into a ***white-dwarf star***. It will then be about 15 billion years old, only 1% of its present size (about the size of Earth), and 0.1% as luminous. The white-dwarf, made entirely of carbon nuclei, will be incredibly dense; about half the present solar mass will be squeezed into a sphere the size of Earth. This density, about 2×10^9 kg/m^3, is roughly what would result if several 1000 kg automobiles were compacted to fit into a thimble. Gradually, over several billion more years, the white-dwarf will decrease in temperature and luminosity and end its life as a cool, dark cinder of carbon known as a ***black dwarf***.

All stars do not become black dwarfs. This end is predicted for smaller stars, with masses of up to about 3 solar masses; larger stars burn through their supply of hydrogen and helium relatively quickly. When the helium is exhausted, the inevitable collapse of the core raises the temperature high enough that fusion of heavier elements can occur. Eventually, the first 26 elements, up to iron, are produced. There is no way for thermonuclear fusion to continue beyond iron. As the core clogs up with iron, the star cannot generate more energy. With no pressure to counteract the effects of gravity, a third collapse begins, and eventually electrons and protons are forced together to form neutrons. The star finally stabilizes and ends its life as a small ***neutron star***, only about 16 km in diameter and with a density on the order of a billion billion kg/m^3.

In even larger stars, the collapse of the iron-filled core happens so rapidly that the star literally tears itself apart in a massive explosion known as a ***supernova***. This is the most spectacular stellar event known. For several days the star emits more energy than an entire galaxy . During the supernova, temperature and pressure are so high that all of the elements up to uranium and plutonium are created and then hurled out into space. It is believed that in the early history of the universe, many large stars formed, became supernovas, and synthesized all of the known elements. These elements were then incorporated into new generations of stars, some of which became supernovas and formed more heavy elements. This process occurs repeatedly so that the concentration of heavy elements in the universe continues to increase. Within the Sun we can see traces of all of the elements, and it is presumed that everything heavier than iron was formed previously in a supernova.

During the supernova process, the core of the star is crushed into a mass of neutrons. The remaining neutron star is only about 16 km across and spins rapidly on its axis, typically 20 to 50 times per second. The star's original magnetic field has been concentrated by the collapse and is now extremely strong. Electrons spiraling in toward the north and south magnetic poles of the rotating star produce radio waves in a narrow beam that flash out from the magnetic poles of the star. As the star spins, this beam acts like the beam of a beacon light similar to the flashing light on top of a police car. When these pulsating radio signals were first detected on Earth in the 1960s, it was thought that they might be coded signals from some intelligent life form, and the objects were humorously referred to as LGM (little green men). We have now detected more than 500 of these rotating neutron stars, known as ***pulsars***.

The most massive stars are thought to have an even stranger fate. Because of the very large mass and associated gravity, the final collapse of the star cannot be stopped. The star collapses into itself and forms a ***black hole***. The nature of space and time near a black hole is not fully understood, but mathematical models have been developed which suggest that there are several types of black holes; as yet, a black hole has not been definitely observed. The concept of the black hole goes back to at least 1783, when John Michell speculated on the existence of a star with such strong gravity that no light could escape from it. Astronomers have now detected several dark regions of space that emit x-rays. It is thought that these x-rays are produced as electrons accelerate into a black hole. It is interesting to speculate about where matter goes after it disappears into a black hole. Some scientists believe that the black hole can eventually fill up and return as normal matter, while others have suggested that perhaps a black hole has another side, a white hole, where matter spontaneously appears in space. Perhaps the black hole is a portal to another universe, or a shortcut to a distant location in our own universe (a wormhole). It has been theorized that strange things like these may exist near the center of galaxies.

Much of our knowledge of stellar evolution—the birth, life and death of stars—is based on observations of the Sun. For astrophysicists, the Sun is a magnificent laboratory for the detailed study of stars. But as we have looked more closely at the Sun over the last few decades using space-based instruments, a complex and mysterious picture has emerged. The turbulent surface atmosphere that we observe, with its contorted and dynamic magnetic field structures, is still highly unpredictable. Although we know more about the Sun every day, there are many unanswered questions, and new ones arise constantly.

Problems and Questions

1. (a) How many stars are in our galaxy and how is it possible to estimate this number? How accurately is this number known?

   (b) About how many galaxies seem to be in the universe?

   (c) How long would it take to count up to this number at the rate of one number per second?

   (d) About how many stars are in the universe?

   (e) Estimate the mass of all the stars in the universe.

2. Explain what a Sun-year is and why we say that the Sun is now about 22 years old. How many years old will the Sun be:

   (a) when it exhausts the hydrogen fuel in the core?

   (b) when it becomes a red giant and engulfs Mercury?

   (c) when it is a white dwarf?

3. Notice that Figure 1–2., showing the life of the Sun on a Hertzprung-Russell diagram, does not have a time axis. How could time be shown?

4. Assuming that the proto-solar nebula had uniform density out to 5 AU (Jupiter's present orbit) and rotated with a period of 12 years, find the new rotational period as the sun collapsed to its present size. Hint: use conservation of angular momentum.

5. (a) What elements are present in the Sun and in roughly what proportions?

   (b) What elements can be formed by the nuclear fusion processes inside the Sun, a small star?

   (c) What elements can be formed inside larger stars?

   (d) How are elements heavier than iron formed?

6. What are the possible ways that a star can end its life?

Chapter 2

The Structure of the Sun

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

Section 1.—The Interior

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

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

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

Section 2.—Thermonuclear Fusion

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

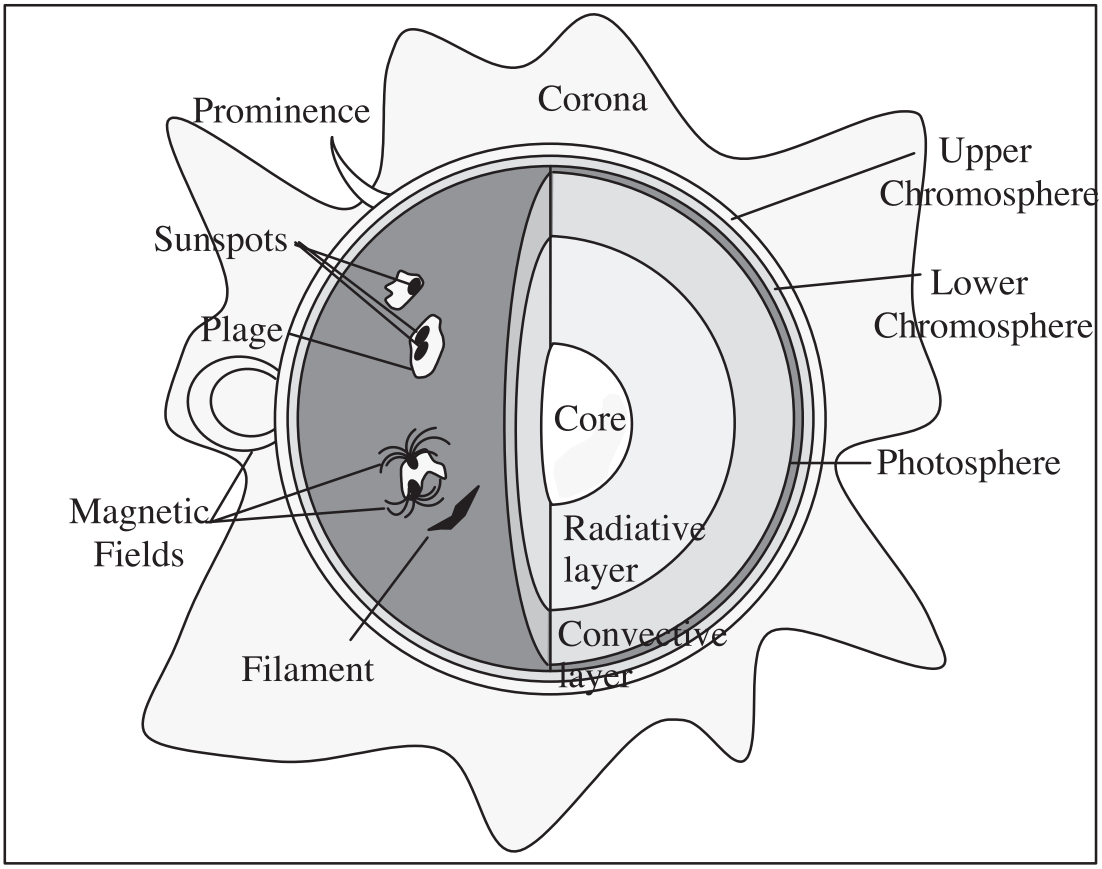


Figure 2–1.—*The structure of the Sun*

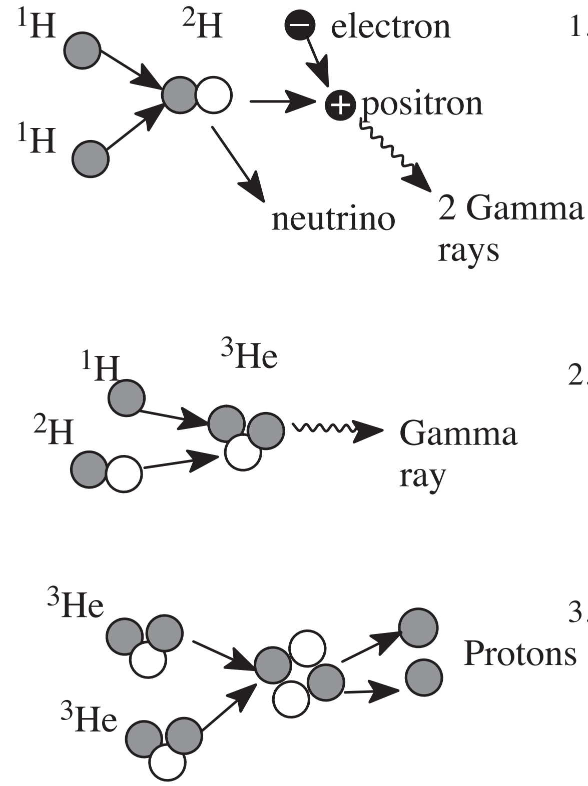
Hydrogen-helium fusion can occur in more than one way, but in any case the temperature must be in the vicinity of 15 million K so that two positively charged particles will be moving fast enough to overcome their electrical repulsion when they collide. The density must be large, and the immense solar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

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

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

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

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



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

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

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

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

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

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

Section 3.—The Surface Atmospheres

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

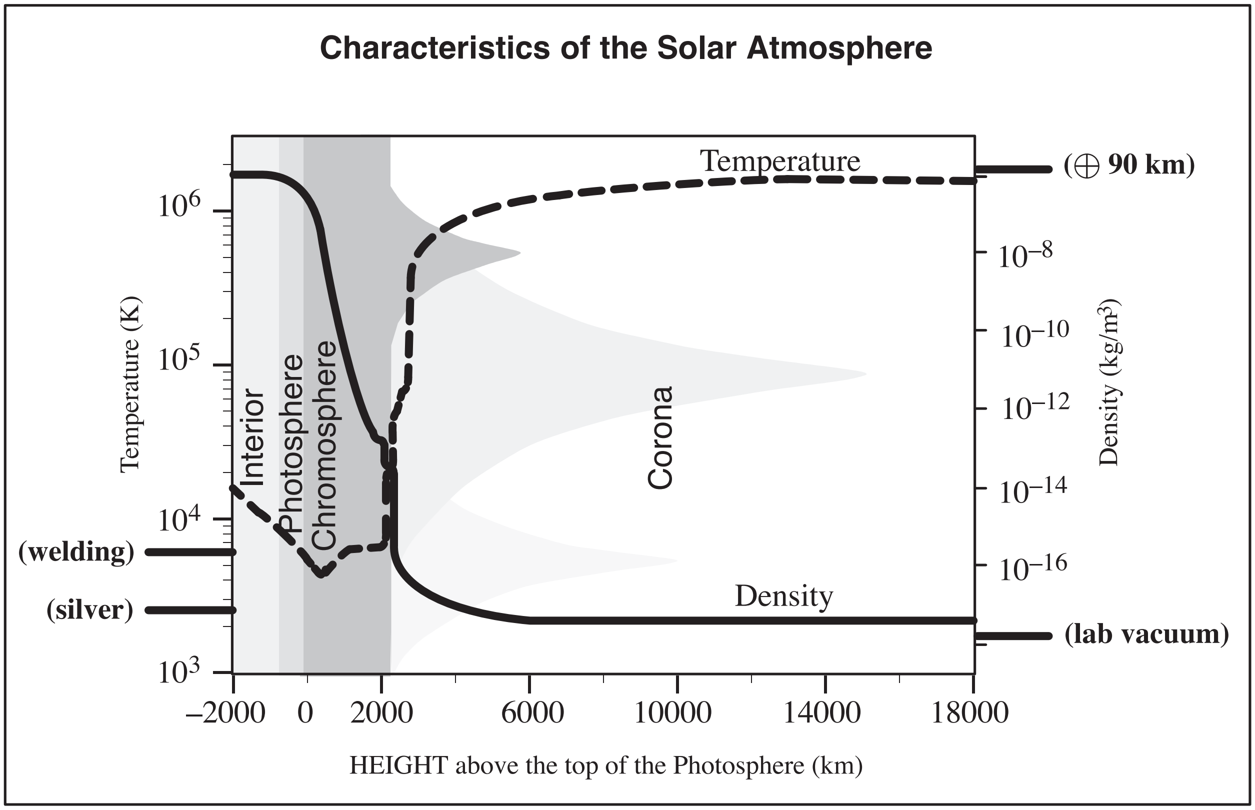


Figure 2–4.—*Temperature (dashed line) and density (solid line) of the of the Solar Atmosphere. Note that the highest density on the scale here is still only as dense as the Earth's atmosphere at 90 km up. The melting temperature of silver is near the bottom of the temperature scale shown here. (after*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

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

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

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

Table 2–1. — The Sun's Vital Statistics

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

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

These periods can easily be determined by watching sunspots over several days (Figure 2–5). It is now known,

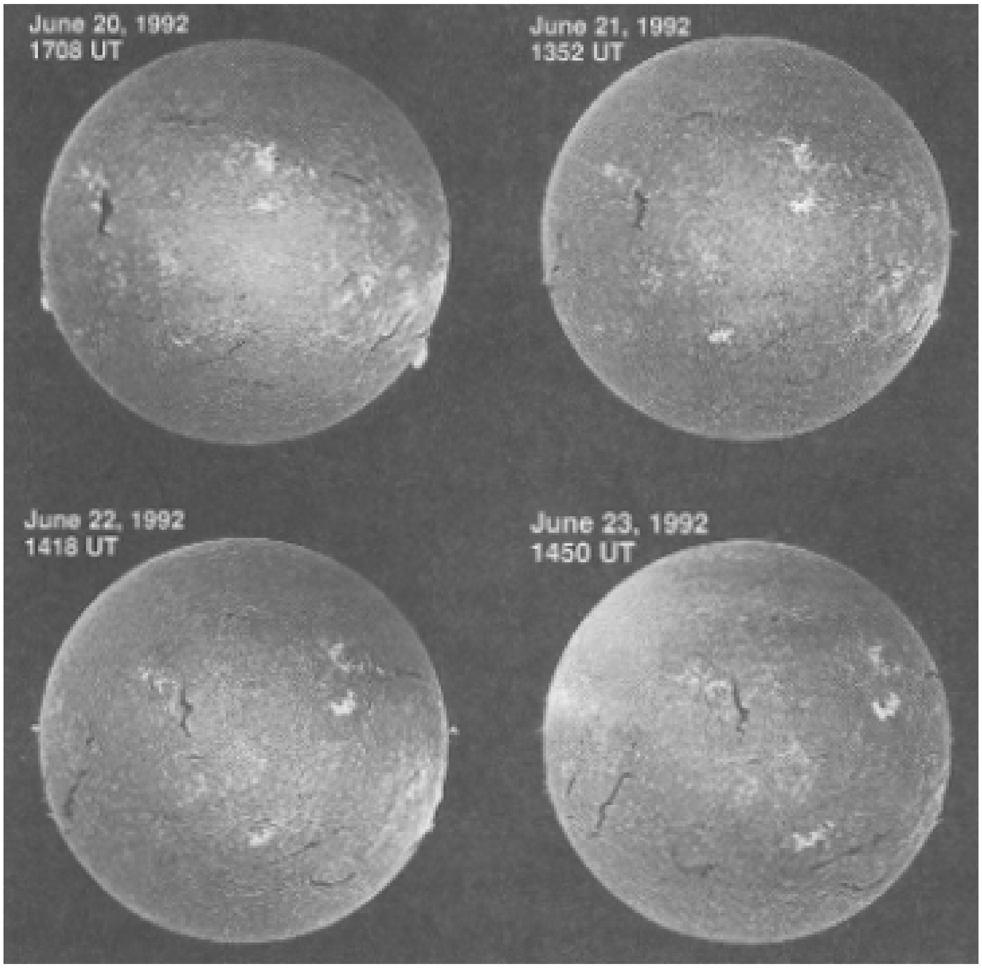


Figure 2–5.*—Photos of the Sun on four consecutive days taken in Hα light. Features can be seen to move as the Sun rotates.*

however, that these periods correspond to the photosphere where the sunspots reside, and that the rotational period varies in the different layers above the photosphere. This complicated variation of rotational period according to latitude and depth contributes to the shearing and twisting that give rise to solar activity.

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

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

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

Section 4.—The Inner Corona

The inner corona is the wispy halo, extending more than a million kilometers out into space, that can be seen when the brilliant disk of the Sun is blocked by the Moon during a total eclipse (Figure 2–6). The cause of the high temperature of

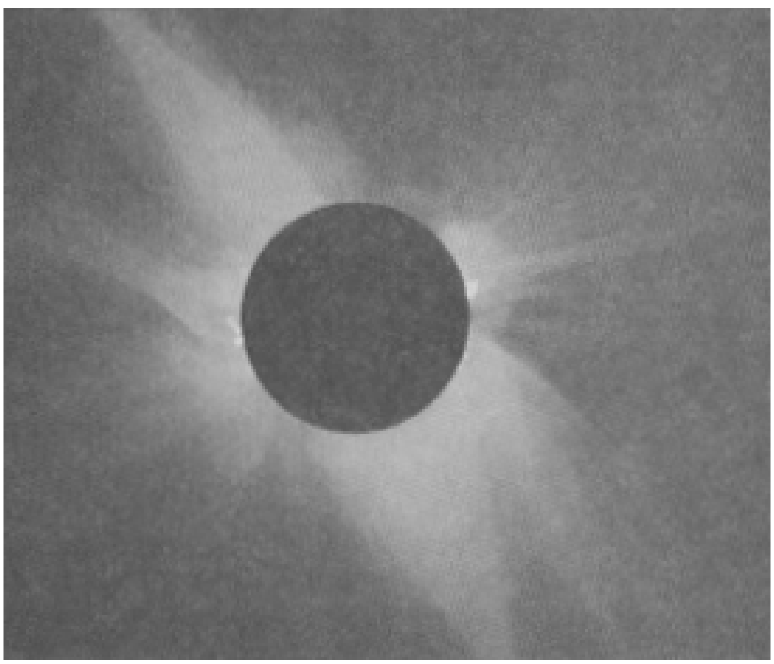


Figure 2–6.—*Total solar eclipse of July 11, 1991 as seen from Baja California. This digital mosaic is derived from five individual photographs by Dennis DiCicco (Sky and Telescope) and Gary Emerson (E. E. Barnard Observatory); digitized by David Sime, NCAR's High Altitude Observatory; processed by Steve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

the corona, about 2,000,000 K, is not well understood. The corona is a large source of x-rays which do not penetrate Earth's atmosphere. With instruments on satellites we can look at the corona in x-ray wavelengths and see many details that do not appear in visible light. From this vantage point it is clear that magnetic arches dominate the structure of the corona. Large and small magnetic active regions glow brightly at x-ray wavelengths, while open magnetic field* structures appear as gaping ***coronal holes***. The coronal material is generally confined by closed magnetic field structures, anchored at both ends, but the open field structure of coronal holes allows the corona to escape freely to form fast, low density streams in the ***solar wind***. This material travels outward and causes disturbances in Earth's magnetic field. Because of their effects on Earth, we would like to be able to predict when and where coronal holes will form, but as yet we cannot do this.

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

Section 5.—The Outer Corona

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

In the 30 years since the discovery of the solar wind, we have learned much more about it, and its effects on Earth. The solar wind streams radially outward from the Sun. Solar rotation swings the source around so that the individual streams describe ***Archimedian spirals*** (Figure 2–7); the solar wind speed and density vary according to the conditions

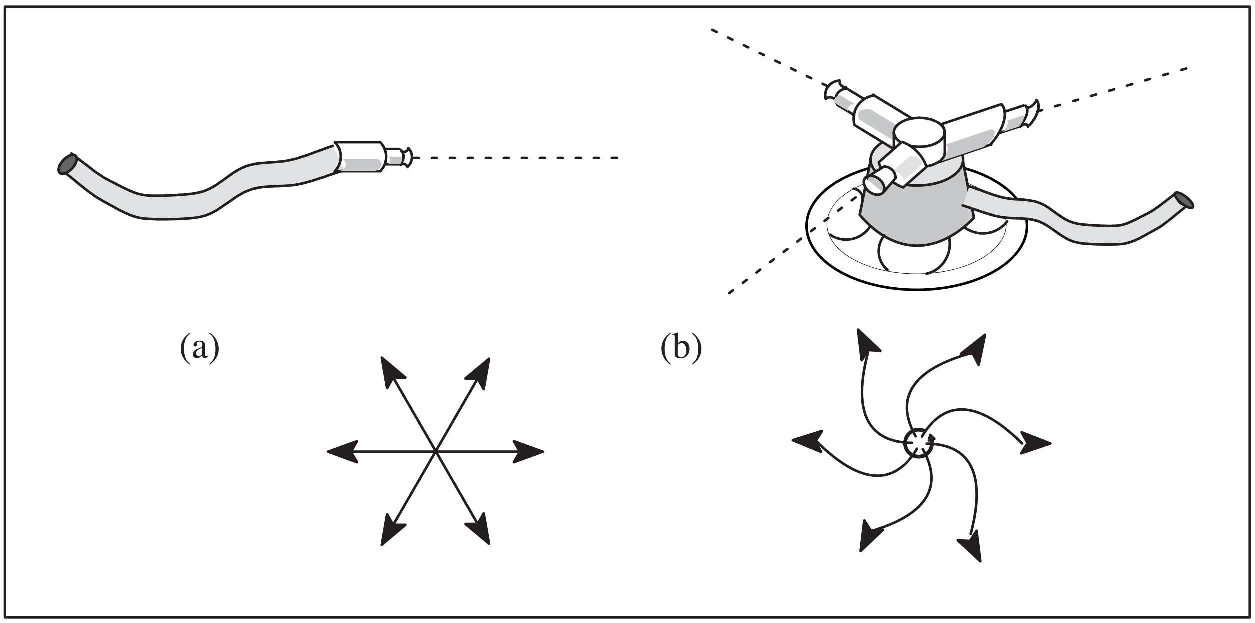


Figure 2–7.—*(a) The pattern that particles in the solar wind would make if the Sun did not rotate; the outflowing wind is radial. An analogy would be a garden hose. (b) The "Archimedes spiral" pattern produced by solar rotation. An analogy would be a garden sprinkler. During the four days that it takes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

on the Sun. This variation in the solar wind intensity began to make more sense after the discovery of coronal holes during the Skylab missions in the early 1970s. Using an x-ray telescope, the Skylab astronauts took many pictures of the Sun which showed coronal holes as large, dark regions with open magnetic field lines where the corona streams outward. These regions grow and shrink, and move around on the Sun in ways that are not yet understood. When a coronal hole is facing Earth, the solar wind reaching Earth is more intense.

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

Problems and Questions

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

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

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.

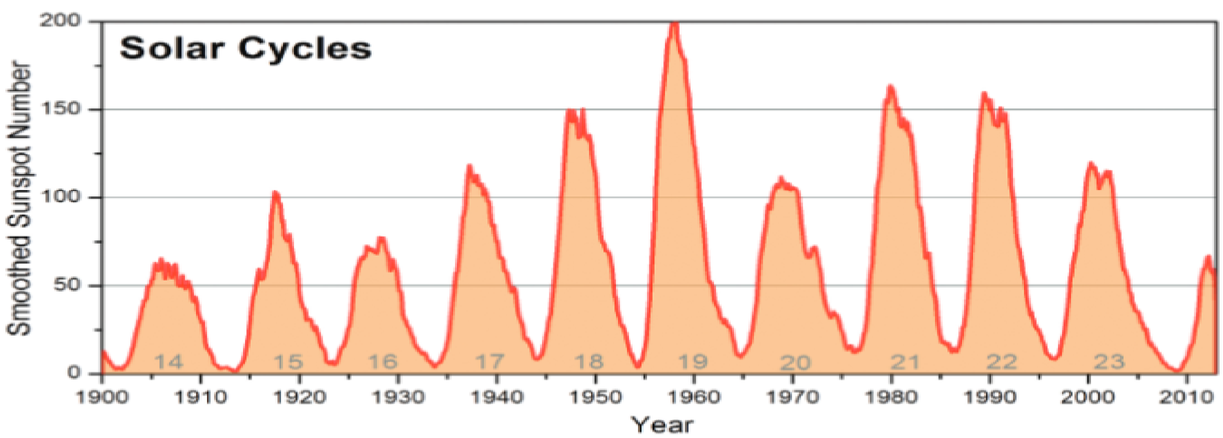


Figure 3–1.—*Sunspot Cycles from 1900 to 2015. One periodic increase and decrease of sunspots defines a cycle. Cycle 23 began in 1996, peaked in 2000 and ended in about 2008.*

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

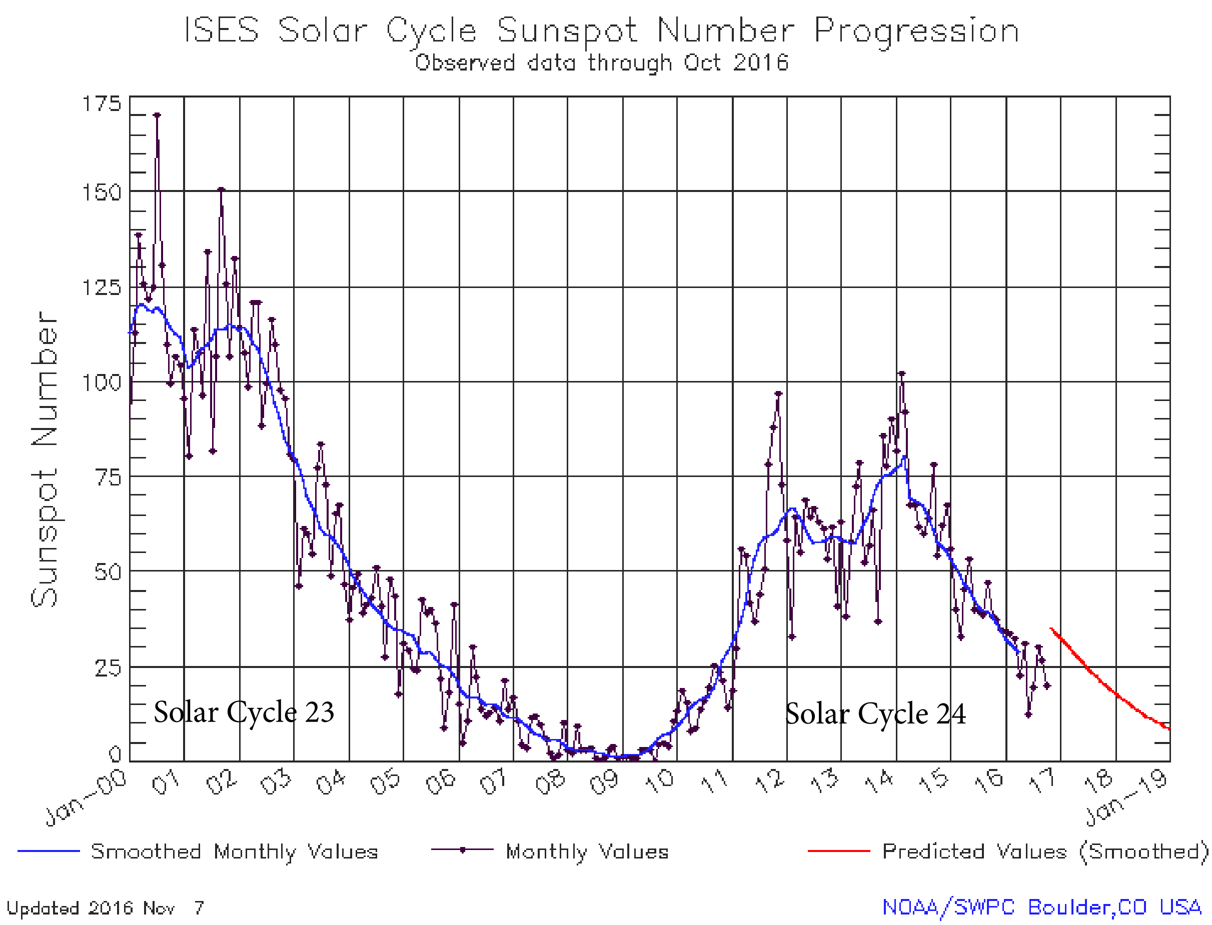


Figure 3–2.—*This SWPC plot shows the actual monthly mean total sunpot numbers, along with a smoothed monthly sunspot value from January, 2000 through October, 2016. These types of plots can help scientists predict how large a current cycle will be or is progressing in relation to a solar cycle forecast.*

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

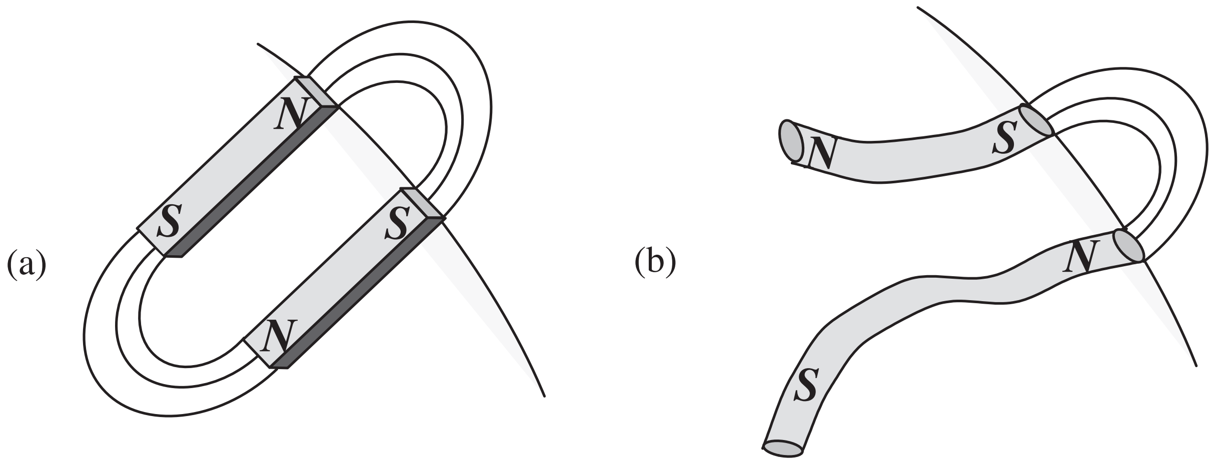


Figure 3–3.—*(a) A pair of bar magnets submerged below the photosphere would produce fields at the surface resembling those of an active region near sunspots. (b) More realistically, flexible magnetic tubes, or flux tubes, probably give rise to the magnetic fields that we see.*

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

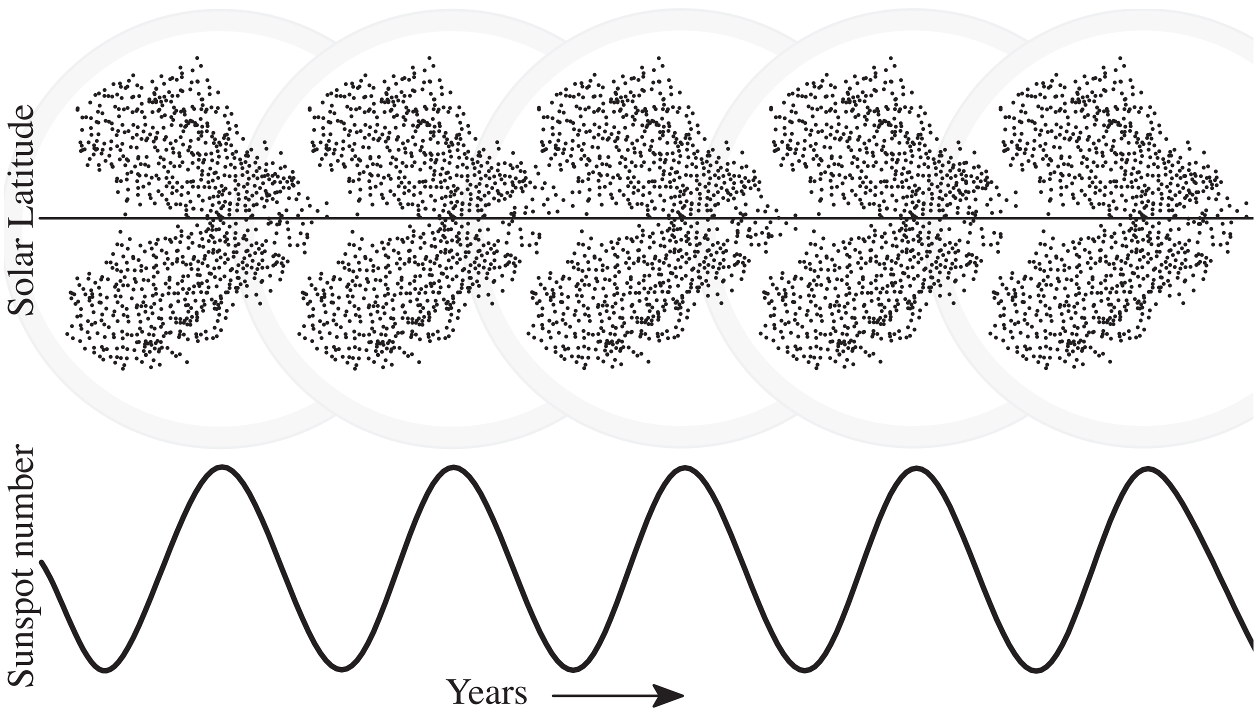


Figure 3–4.—A schematic illustration of the migration of sunspots from higher latitudes toward the equator during each cycle (shown schematically below) is seen in the characteristic "butterfly" pattern. The overlap of the end of one cycle and the beginning of the next can also be seen.

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

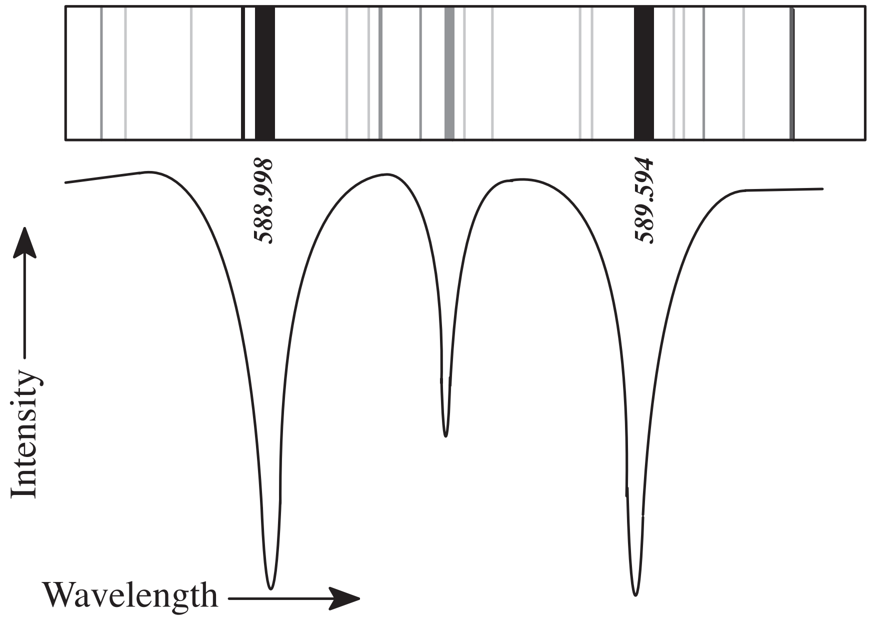


Figure 3–5.—Schematic of Sodium absorption from a Solar white-light spectrum. Top: The two dark absorption lines with wavelengths of 589.0 and 589.6 nanometers are produced by sodium atoms absorbing at these wavelengths. Fraunhofer observed these two lines as one, which he named the "D" line. Bottom: 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

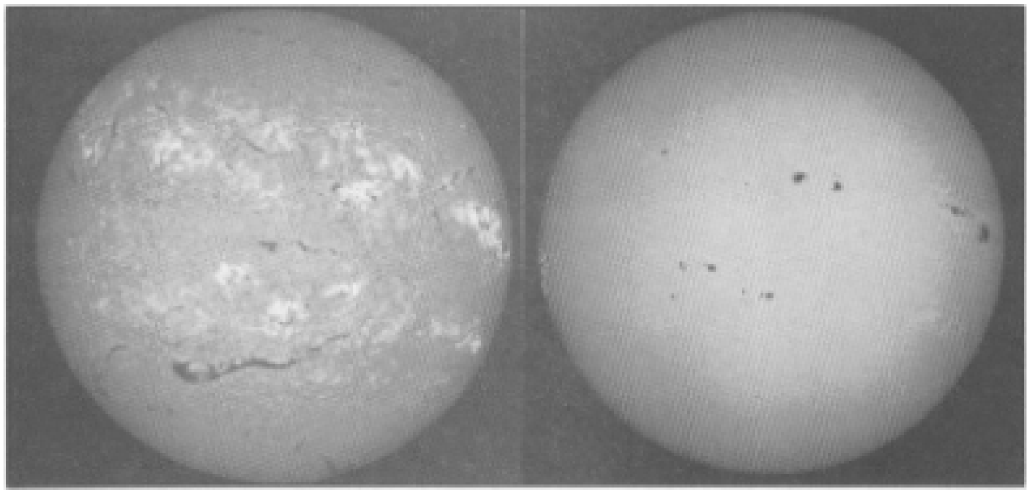


Figure 3–6.—*Two views of the Sun, one photograph taken in white light, one taken in Hα*

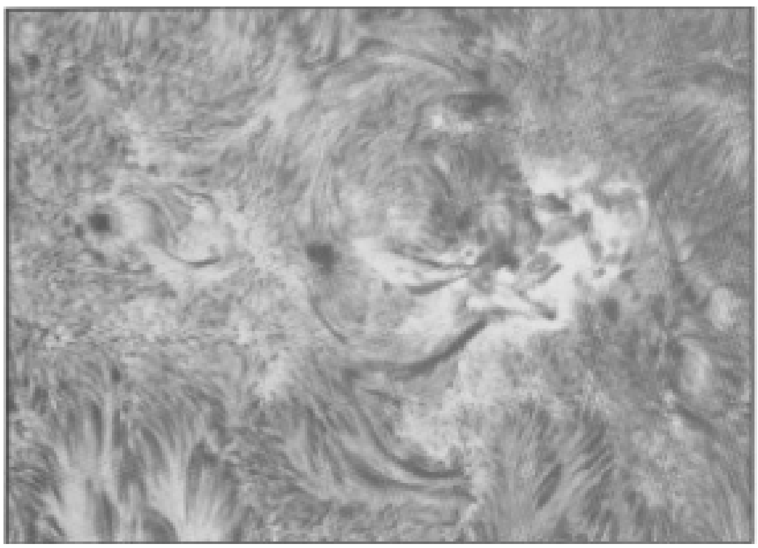


Figure 3–7.—*A close view of the low chromosphere taken in the Hα depicting the fibril structure around a solar region. The bright areas of plage lie above the sunspots on the photosphere. Photo courtesy of Big Bear Solar Observatory.*

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

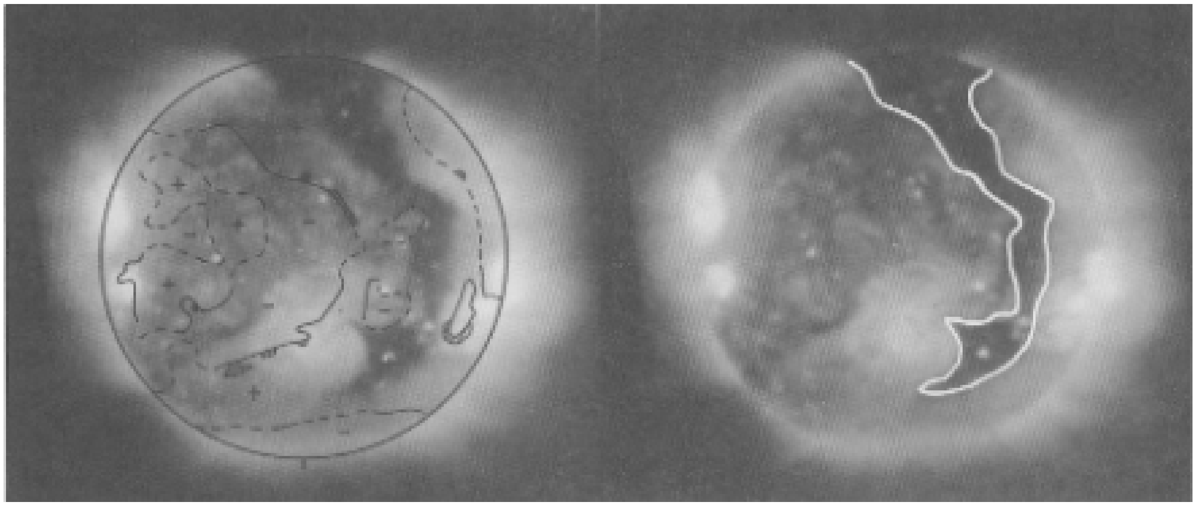


Figure 3–8.—An x-ray image of the Sun taken during the Skylab mission on June 30, 1973. The right photo shows a coronal hole outlined in white. The large boot-shaped coronal hole stretches from the north pole into the southern latitudes. The left photo shows the lines of reversal in polarity of magnetic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

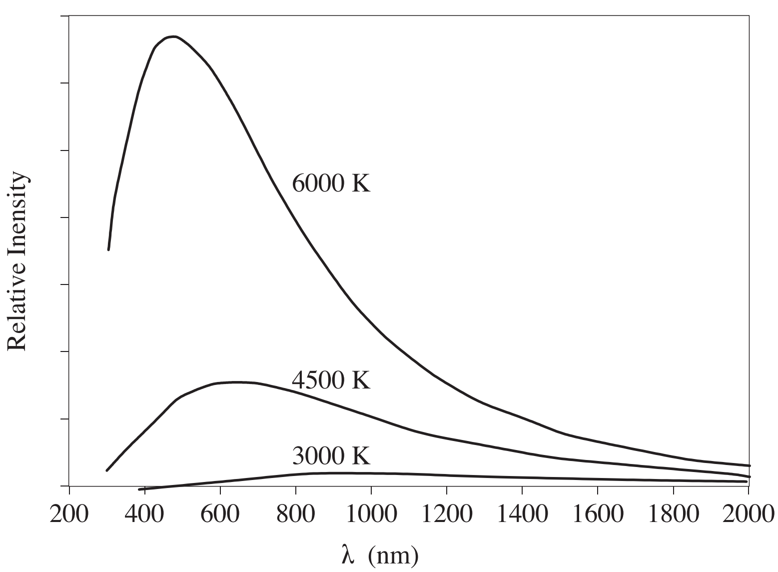


Figure 3–9.*—Schematic blackbody radiation curves at three temperatures. The wavelength of maximum intensity varies inversely with the absolute temperature as in the formula*

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

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***).

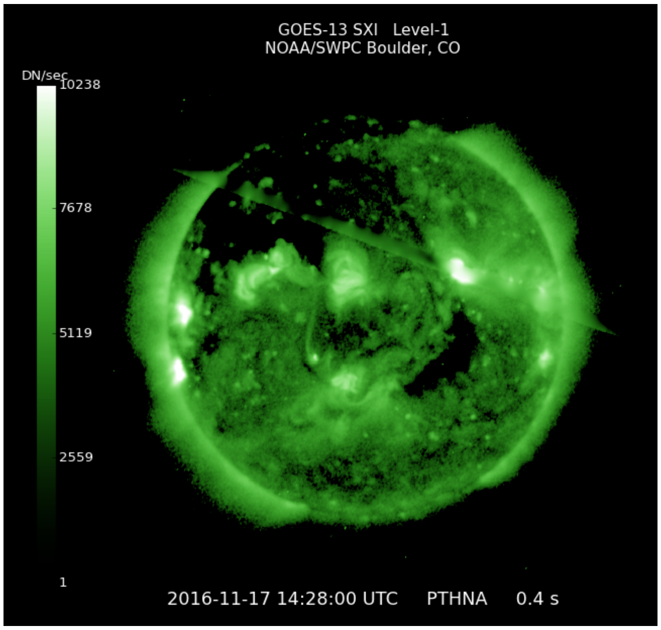


Figure 3–10.*—An x-ray image of the Sun taken in 2016, from the GOES-13 solar x-ray imager (SXI). Various exposure settings are captured throughout a sequence of images taken each minute. This particular image (Level-1) allows a better look at coronal structure; as well as some examination of active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

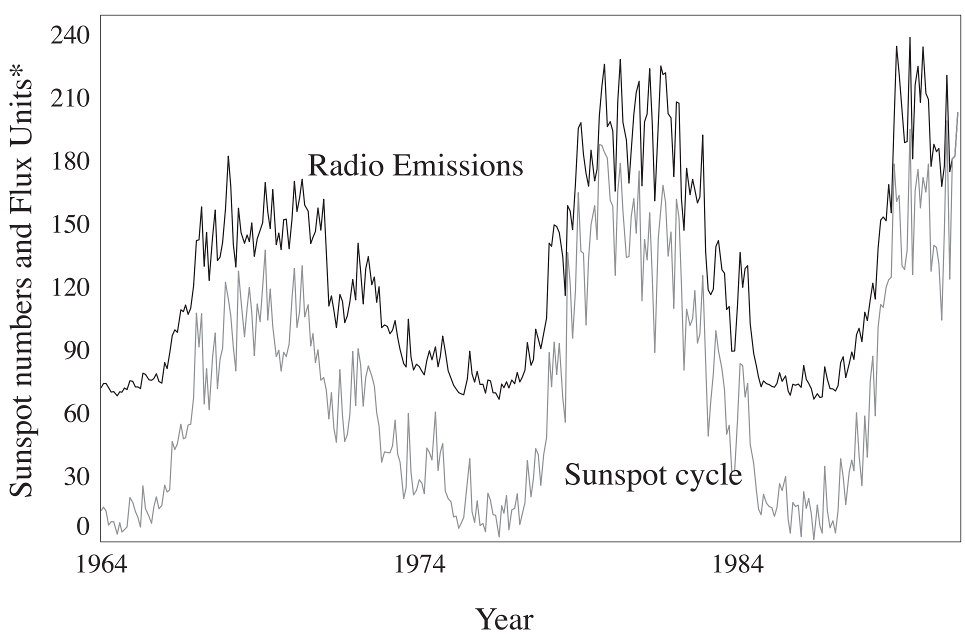


Figure 3–11.*—Radio emission (10.7 cm flux) follows the sunspot cycles fairly well.*

** 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 Hα. What advantages does each have? What features of the Sun can be seen in x-rays but not the white or Hα?
5. Find the the energy level difference (in ev) in the hydrogen atom that produces the Hα 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 (Re = 6.38 x 10^6 m). Hint: this is an estimate that Isaac Newton was capable of in 1660.
13. Why is black body radiation called black?

Chapter 4

Solar-Terrestrial Interactions

Section 1.—The Terrestrial Space Environment

The effects of the radiation and particles that stream out from the Sun would be quite deadly for the inhabitants of Earth if not for two protective features. The first one is Earth's atmosphere, which blocks out the x-rays and most of the ultraviolet radiation. When x-ray or ultraviolet photons encounter the atmosphere they hit molecules and are absorbed, causing the molecules to become ***ionized***; photons are re-emitted but at much longer (and less biologically destructive) wavelengths. The second protective mechanism is the Earth's magnetic field. This protects living organisms from the charged particles that reach the planet steadily as part of the solar wind and the much greater bursts that arrive following mass ejections from the Sun. When charged particles encounter a magnetic field, they generally wrap around the field lines. Only when the path of the particle is parallel to the field can it travel without deflection. If the particle has any motion across the field lines it will be deflected into a circular or spiral path by the Lorentz Force. Most charged particles in the solar wind are deflected by the Earth's magnetic field at a location called the ***magnetopause***, about 10 Earth radii above the Earth on the day side. Inside the magnetopause, the Earth's magnetic field has the dominant effect on particle motion, and outside, the solar wind's magnetic field has control.

Until 1960, Earth's magnetic field, called the geomagnetic field, was thought to be a simple ***dipole field*** like that of a bar magnet. We do not yet know the details of what produces the geomagnetic field, except that there must be currents circulating inside Earth, probably associated with the molten core. With the discovery of the ***solar wind***, physicists realized that the magnetic field of Earth is pushed away from the Sun. The solar wind exerts a pressure on Earth's magnetic field which compresses it on the Sun-facing side and stretches it into a very long tail on the side away from the Sun. This complex magnetic envelope is called the magnetosphere (Figure 4–1). On the Sun-facing side, the solar wind compresses the magnetosphere to a distance of about 10 Earth radii; on the downwind side, the ***magnetotail*** stretches for more than 1000 Earth radii. The magnetosphere is filled with tenuous plasmas of different densities and temperatures, which originate from the solar wind and the ***ionosphere***. The ionosphere is the highly charged layer of Earth's atmosphere which is formed by the ionizing effect of solar radiation on atmospheric molecules. In the early 1960s, solar physicists began to realize that the solar wind carries the Sun's magnetic field out to the far reaches of the solar system. This extension of the Sun's magnetic field is called the ***interplanetary magnetic field*** and it can join with geomagnetic field lines originating in the polar regions of Earth. This joining of the Sun's and Earth's magnetic fields is called ***magnetic reconnection***, and happens most efficiently when the two fields are anti-parallel. Through reconnection the magnetic fields of Sun and Earth become coupled together.

Solar wind particles approaching Earth can enter the magnetosphere because of reconnection and then travel along the geomagnetic field lines in a corkscrew path (Figure 4–2). Positive ions and electrons follow magnetic field lines (in opposite directions) to produce what are called field-aligned currents. The solar wind and the magnetosphere form a vast electrical generator which converts the kinetic energy of solar wind particles into electrical energy. The power produced by this magnetohydrodynamic generator can exceed 10^{12} watts, roughly equal to the average rate of consumption of energy in the United States today! The very complex plasmas and currents in the magnetosphere are not fully understood. Some of the solar wind particles travel back along the magnetotail in currents which make the tail

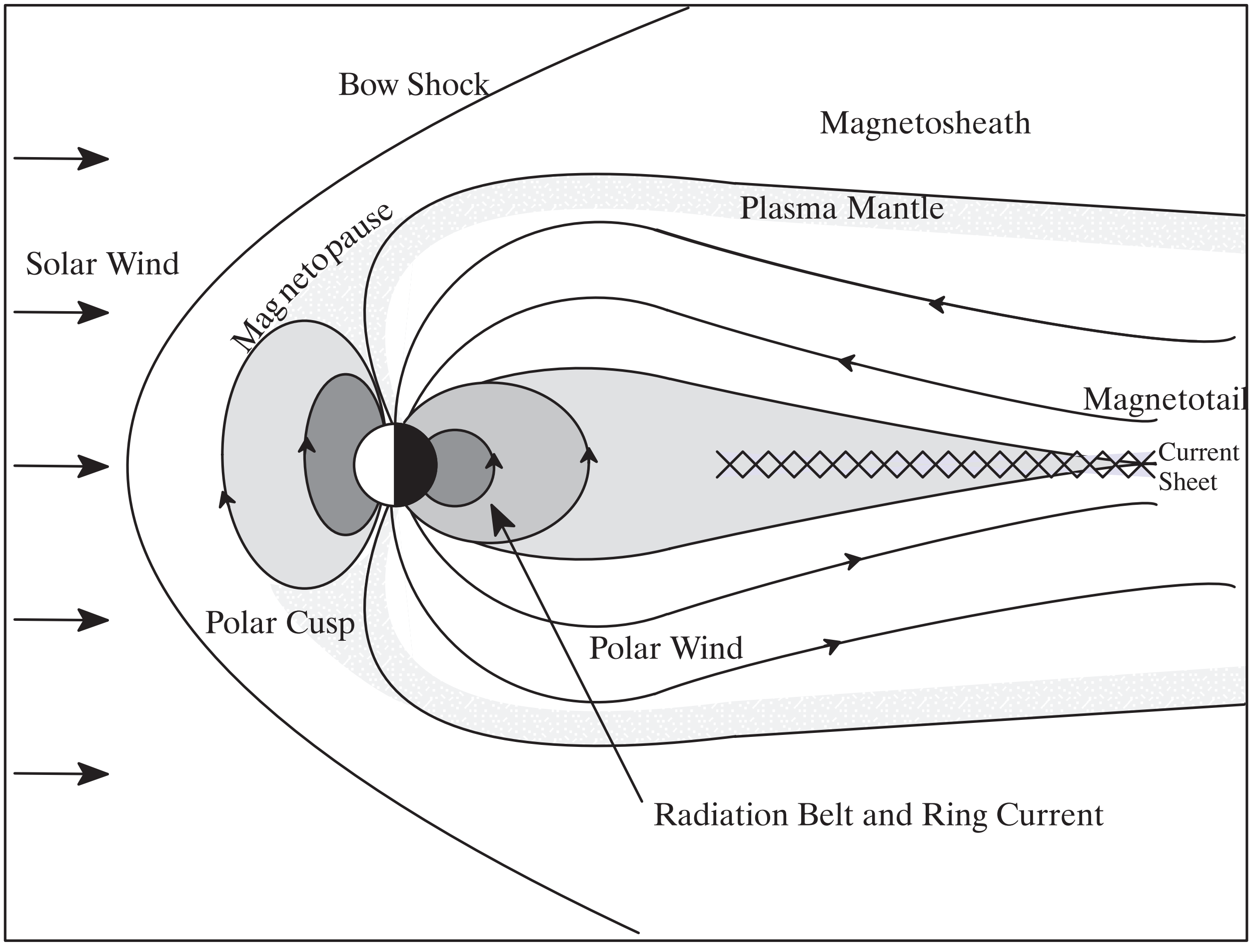


Figure 4–12.*—A "side view" of the Earth and magnetosphere showing some of the important regions.*

look like it has a giant battery in it. Some particles follow the field lines that converge near the polar regions of the earth and bounce back and forth, trapped in a magnetic mirror. Other particles are injected into the ionosphere and form an oval of light around the polar regions of Earth, called the ***auroral ovals***.

The auroras are caused by electrons colliding with molecules in the ionosphere (Figure 4–13). These collisions both ionize the molecules and excite them into emitting a wide spectrum of light from infrared to ultraviolet. The most common auroral emission is a whitish-green light with a wavelength of 558 nm, which is produced by atomic oxygen. A beautiful pink emission comes from excited molecules of nitrogen. The large, moving curtains of color that result from molecular excitation are familiar to people of the far northern and southern latitudes, although they can be seen from anywhere on Earth if the conditions are right. Auroras occur near both the north and south polar regions of Earth, and the two displays are nearly mirror images of each other. The northern lights are called the ***aurora borealis***, while the southern lights are called the ***aurora australis***.

Since the early 1900's scientists have suspected that both the auroras and the variations in the Earth's magnetic field must be caused by some kind of currents which flow in the upper atmosphere. Today we know that there are many currents which flow in the magnetosphere caused by the very complicated interplay between the solar wind and Earth's magnetic field. Although these currents are only partially understood at present, the one that has been studied most extensively is the ***Birkeland current***, which is associated with the auroras. When the solar wind encounters the Earth's magnetic field about 50,000 km above Earth, an ***electromotive force*** (EMF) of about 100,000 volts is generated. This

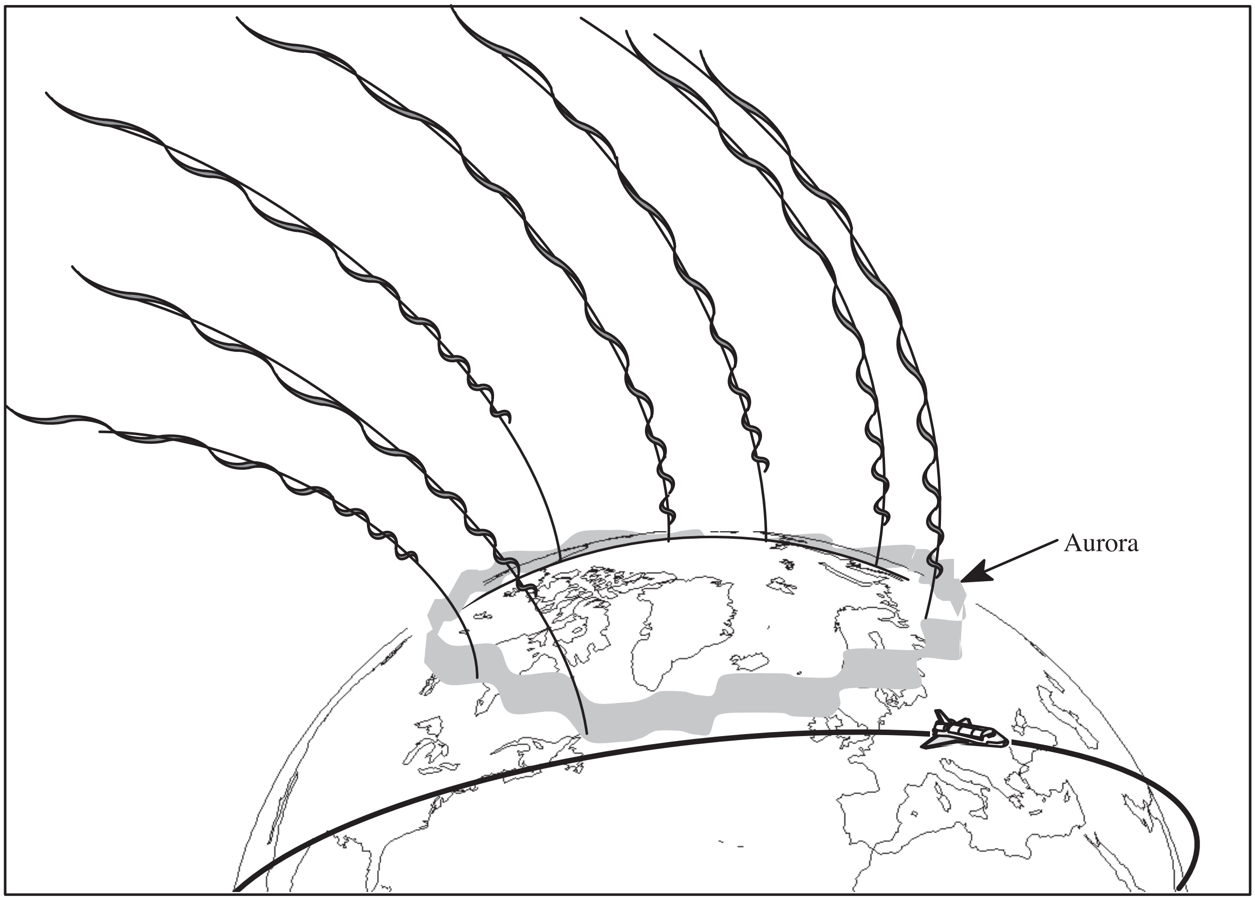


Figure 4–13.—*Energetic electrons travel along the geomagnetic field lines towards the polar regions, striking the upper atmosphere and resulting in the display of lights called aurora.*

applied EMF is distributed throughout the magnetosphere and Earth's upper atmosphere, much as the voltage from a electric utility generator is distributed around a power grid. A portion of the solar-wind-generated EMF, perhaps 10,000 volts, accelerates electrons down magnetic field lines into the ionosphere at altitudes of about 100 km. These electrons first travel horizontally and then back up to the upper atmosphere to form a closed circuit. Although this circuit has many similarities to a simple circuit with wires and a battery, it is also very complex since it occurs in three-dimensional space and varies wildly in time as the solar-wind intensity changes. Currents as high as one million amperes are common, and the total power produced in this giant generator can be as much as 3×10^{12} watts! It is the high-speed electrons near the bottom of this current loop which collide with molecules and atoms of the atmosphere that produce the auroras. The strongest auroral emission comes from altitudes of about 100 km. As with any simple circuit, energy is dissipated as the electrons flow around the loop. Some of this energy shows up as the light of the auroras, but most of it becomes thermal energy—heating the atmosphere. Another important result of the Birkeland current is that, like any current loop, it produces a magnetic field. This field extends down to the Earth's surface where it adds to the geomagnetic field, causing it to fluctuate (see Activity 7). These fluctuations in magnetic field can then induce currents in the Earth's surface, or in conductors like power lines or pipelines. All of this is determined by the behavior of the solar wind reaching Earth, which in turn is determined by the events taking place on the Sun. When the auroras are highly visible, often it is a sign that there is a higher flux of particles from the solar wind. It also means that many of our electronic systems on Earth may become disrupted or even damaged.

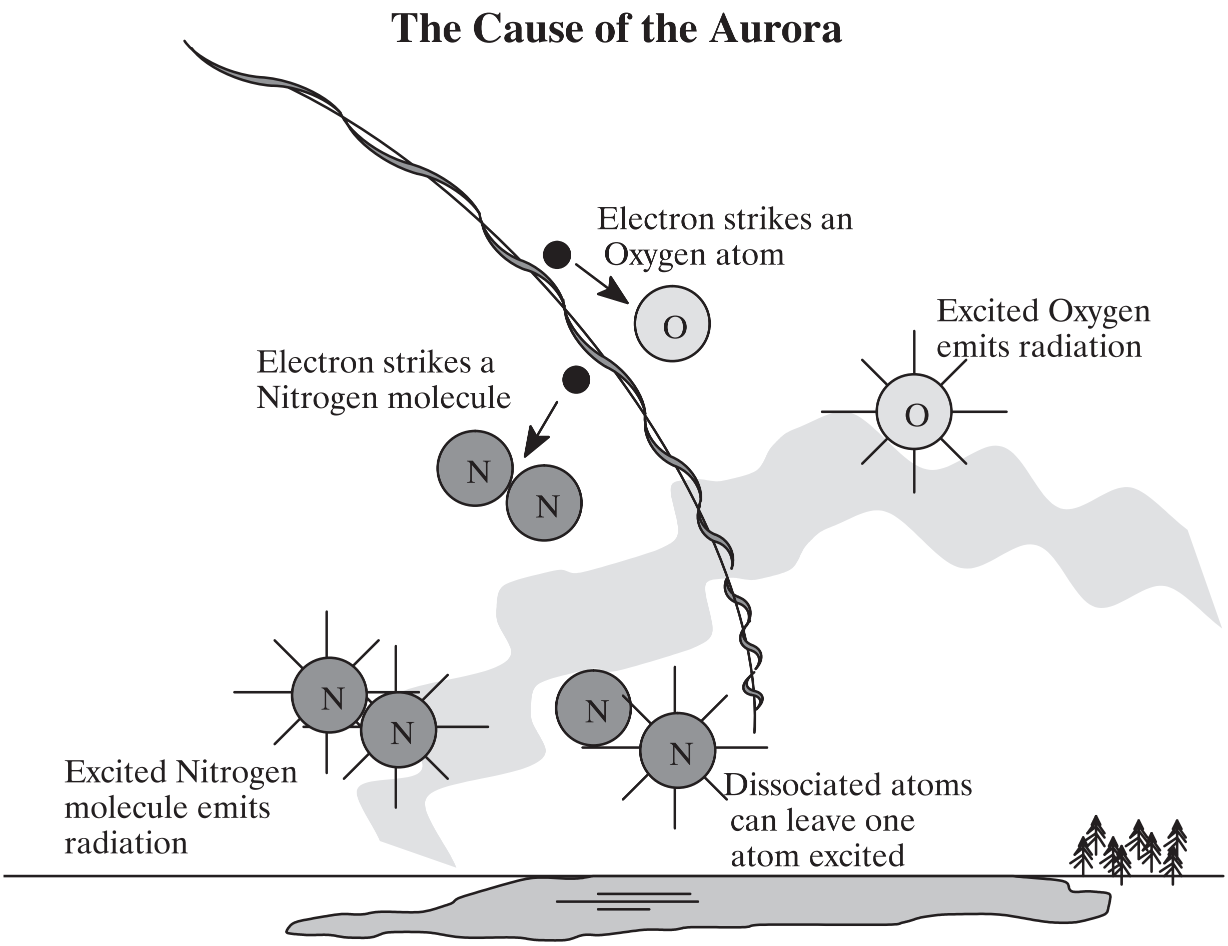


Figure 4–14.—High-speed electrons strike atoms and molecules in the lower ionosphere, causing them to emit visible light seen as the aurora.

Section 2.—Terrestrial Effects

The complex coupling of the solar wind and the geomagnetic field produces many effects near Earth. Earth is embedded in the outer atmosphere of the Sun and therefore is affected by events which occur in the surface layers and coronal regions of the Sun. Terrestrial effects are the result of three general types of conditions on the Sun: eruptive flares, disappearing filaments and coronal holes facing Earth.

Flares are short term brightenings that last for minutes or hours. They usually occur near active regions on the Sun where abrupt changes in magnetic field are taking place. A complete understanding of the conditions and sequence of events associated with flares is still lacking, but generally when a flare begins, plasma is accelerated out from the Sun. This plasma usually returns in an arching fashion and, upon colliding with the denser material of the chromosphere, emits ***Bremsstrahlung x-rays***. In more eruptive flares, plasma is thrown completely away from the Sun, and this radiation can have a significant effect if it reaches the Earth environment.

Long-term eruptive activity is usually associated with the disappearance of ***filaments***. Filaments are the long, string-like features which appear prominently in Hα photos of the Sun (Figure 3–6). They hang like clouds in the low chromosphere for days or weeks then disappear, in most cases by dissipating, much like Earth clouds “burn off.” In other cases, though, filaments disappear by rising up, away from the chromosphere to form giant arching prominences.

When prominences appear at the limb of the Sun, where we can see them from the side, spectacular photos can be taken. In some cases prominences break away from the Sun and large bursts of plasma are hurled outward into space.

The third source of mass traveling out from the Sun is the ***coronal hole***, easily seen as a dark region in an x-ray photo of the Sun (Figure 3–10). Magnetic field lines extend outward from coronal holes, in contrast to other regions of the Sun where field lines arch back to connect (Figure 3–3). The open field structure of coronal holes acts like a conduit for low density plasma which streams out steadily. Coronal holes reside permanently near the poles of the Sun, and the solar wind streaming out from these generally does not reach the Earth. But during some rotations of the Sun, coronal holes form at lower latitudes, facing the Earth (Figure 3–8), and these act like a broadly focused fire hose spraying the Earth with a high intensity of charged particles.

We now know that mid-latitude coronal holes (usually occurring during the phase of solar activity following solar maximum) are sources of high-speed solar wind streams, which buffet Earth in synchronism with the 27-day solar rotation. Previously the cause of these recurring geomagnetic storms was unknown, so the regions were called M-regions, M for mysterious. Non-recurrent major storms and large geomagnetic storms are almost always associated with coronal mass ejections (CMEs) and with the shock waves associated with CMEs.

Several centuries ago, the disruptive effects of the Sun were totally unnoticed by humans. But as technology developed that utilized currents, conductors, and eventually electromagnetic waves, the disruptive effects of the Sun became evident. Early telegraph systems in the 1800s were subject to mysterious currents that seemed to be generated spontaneously. It was not until World War II, when radio communications were heavily relied upon, that solar disturbances were recognized as a serious problem. From that time on, our reliance on electronic technology has grown exponentially and so has the disruptive potential of the Sun. The massive collapse of the Hydro-Quebec power system in 1989, which resulted in the temporary loss of 9450 megawatts of electrical power, probably marked the moment when more than just the scientific community took solar disturbances seriously. A few of the major effects that are a problem today are described below.

Geomagnetically Induced Currents

When an intense surge of solar wind reaches Earth, there are many changes which occur in the magnetosphere. The day side of the magnetosphere is compressed closer to the surface of Earth and the geomagnetic field fluctuates wildly. This type of event is generally called a ***geomagnetic storm***. During a geomagnetic storm the high-latitude currents which occur in the ionosphere change rapidly, in response to changes in the solar wind. These currents produce their own magnetic fields which combine with Earth's magnetic field. At ground level, the result is a changing magnetic field which induces currents in any conductors that are present. These are called geomagnetically induced currents, which often flow through the ground unnoticed by humans. But when good conductors are present, like pipelines and electrical power transmission lines, the currents travel through these as well. These currents are the result of voltages that are induced during geomagnetic storms. Voltages as high as 10 volts per mile have been measured. Although this may seem small, it leads to a potential difference of 10,000 volts in a 1000 mile long pipeline or power line. In 1957, voltage differences of 3,000 V were recorded along a trans-Atlantic cable between Newfoundland and Ireland.

Induced currents are much more serious at higher latitudes, near the auroral oval, and in areas which lie above large deposits of igneous rock. Because igneous rock has a low conductivity, the induced currents tend to take a path through man-made conductors. In pipelines, these currents cause increased corrosion and the malfunction of flow meters. The Alaska pipeline has carried as much as 1000 A during geomagnetic storms. In large power systems, like Hydro-Quebec, surges of induced current overload transformers and capacitor banks, causing damage and shutdown. The problem is worsened by the fact that geomagnetically induced currents are largely direct current, while all of our power systems are alternating current. Hydro-Quebec was especially vulnerable because it is located fairly far north and it sits above huge igneous rock formations. Since 1989 power companies have become very concerned about geomagnetic storms. With better warning, power plants can protect themselves to some extent, but there is still a high degree of vulnerability. Electrical engineers are attempting to design protective mechanisms, but as we build bigger power systems, with more miles of transmission lines, our vulnerability increases.

Communications

Many of our communication systems utilize the ionosphere to reflect radio signals over long distance. Because the ionosphere is altered during geomagnetic storms, these reflected communications are often distorted or completely fade out. Although TV and commercial radio broadcasts are rarely affected, longer distance communication, like ground-to-air, ship-to-shore, Voice of America, and amateur radio, are frequently disrupted. A number of military systems, like early warning, over-the-horizon radar, and submarine detection, are greatly hampered during times of high solar activity. Some types of radio communication can be “jammed” by increased levels of radio output from the Sun. The jamming of air traffic control frequencies can create dangerous situations for air travelers. There are also many navigation systems that are in widespread use today that are vulnerable to solar disturbances. Airplanes and ships use signals from transmitters located around the world to triangulate their positions. Solar activity can cause these systems to give location information that is inaccurate by several kilometers. If navigators are alerted that a proton event or geomagnetic storm is in progress, they can switch to a backup system.

Satellites

Satellites are placed in orbits that are above most of Earth’s atmosphere so that there is little frictional drag affecting them. Communications satellites, in geosynchronous orbits, are about 6 Earth radii up. Low-orbiting satellites, which speed around the earth every 2 hours or so, are barely above the Earth’s atmosphere. During times of high solar activity there is an increase in ultraviolet radiation and auroral energy input, and this heats up Earth’s atmosphere, causing it to expand. The low-orbiting satellites then encounter increased drag which causes them to drop in their orbits. Satellites with propulsion systems, and the fuel to run them, can be raised back to their correct orbits, but some of the satellite orbits will decay causing them to fall to Earth; this was the fate of Skylab. The high satellites, in geosynchronous orbits, are not subject to drag from atmospheric heating, but they are subjected to the solar wind. These satellites are usually well protected from solar wind particles by the magnetosphere which normally has a minimum thickness of about 10 Earth radii. But when a surge in the solar wind reaches Earth, the front side of the magnetosphere can be compressed or eroded away to a thickness of about 4 Earth radii. This places the high satellites outside the protective shield of the magnetosphere. The impact of high speed particles has a corrosive effect on satellites, and charge buildup can result from these particles. Electrical discharges can arc across spacecraft components causing damage.

Biological Effects

For much of the world’s population, living in the mid-latitudes, there is probably very little direct effect when solar activity occurs. Protons and electrons do not reach Earth’s surface because of the shielding of the magnetosphere. However, aircraft flying high altitude polar routes are subject to a greater flux of protons because the magnetic shielding is weak near the poles. It is not yet known how serious this is for passengers, but some experts advise pregnant women not to fly on polar routes during times of high solar activity. There is also great concern for the safety of astronauts during solar proton events. Astronauts during the Space Shuttle program were fairly safe because the Shuttle stayed in a relatively low orbit, well protected by the magnetosphere. The spacecraft itself provided good shielding from particles, but when astronauts were outside the spacecraft, they were in much greater danger. Energetic protons can penetrate deep into the magnetosphere and potentially expose astronauts to a dangerous dose of radiation during the very rare, intense radiation storms. Space missions which go outside the magnetosphere, like Moon or Mars missions, will have to deal with the problems of solar disturbances. A trip to Mars will take 2 to 3 years, and the problems of exposure to solar effects will be significant. The International Space Station (ISS) has been in low Earth orbit since 1998 and continuously occupied since late 2000. Astronauts occasionally must work outside for long periods of time, and can become vulnerable to solar radiation. The ability to predict dangerous energetic proton (radiation storm) events, and give advanced warning is one of our most powerful protections.

There are a number of other biological effects, some substantiated and some not. It is well known that many animals use Earth's magnetic field to navigate. This explains how migratory birds can fly thousands of kilometers across oceans and not get lost. It is not known exactly how these animals can detect Earth's field, but studies on homing pigeons have shown that there are certain tissues in the head and neck regions that contain iron-rich molecules with magnetic properties. What is known with certainty is that animals with magnetic navigational abilities tend to become disoriented during geomagnetic storms when the geomagnetic field fluctuates. Some researchers are beginning to suspect that humans are susceptible to magnetic effects. A correlation has been made in Israel between solar activity and a higher death rate for heart disease patients who are near death. Studies in Hungary claim a correlation between high solar activity and increased industrial and traffic accidents. There are even people today who are looking for correlations between solar activity and the stock market. Apparently no one has yet gotten rich from this tenuous connection!

Section 3.—Forecasting and the Future of Solar Physics

Serious interest in being able to predict solar activity, and its effects on Earth, began during World War II. Electronic technologies, such as radio communication, radar, and magnetic submarine detection, were heavily relied upon for the first time and it became clear that these technologies could be seriously disrupted by the Sun. After the war, more uses were developed for electronic technologies, especially with the birth of the space program. During the 1950s, there were attempts to pool resources world-wide to improve forecasting, but this was to end in the late 50s with the launch of the Soviet Sputnik and the beginning of the cold war. Anticipating the Moon mission of 1969, NASA became heavily involved because of the danger to astronauts. This reached a peak in 1973 with the Skylab missions. Since that time, financial support for solar research has decreased, yet our need to be able to forecast solar activity continues to increase as vulnerable technologies become more widespread. Undoubtedly, the power outage at Hydro-Quebec in 1989 underscored the importance of solar forecasting.

In the early days of solar forecasting, it was assumed that when a CME occurred from the Sun there would be a very predictable geomagnetic disturbance on Earth within a few hours or days. It was therefore believed that improved forecasting was just a matter of making better observations of the Sun so that flares and other mass ejections could be detected immediately after they occurred. But experience soon showed that the effects on Earth did not correlate so simply with events on the Sun; not all mass ejections had a noticeable effect on Earth, and sometimes there were geomagnetic storms when there was no apparent eruptive activity on the Sun.

We now know that how the Sun's magnetic field connects with the geomagnetic field makes a big difference in how solar activity affects Earth. When a mass of plasma is ejected from the Sun, the plasma travels outward in the solar wind. These plasma bursts have their own magnetic fields which are carried along with the plasma. How these fields are oriented when they arrive at Earth determines whether magnetic reconnection will occur. When the direction of the solar wind field is opposite the direction of Earth's field, magnetic reconnection occurs, and the ***geomagnetosphere*** essentially becomes a part of the solar magnetic field. In this condition, Earth is much more prone to the effects of the solar wind. Solar wind particles can enter the magnetosphere more easily, and those already within the magnetosphere are energized. Changes in solar wind magnetic fields cause wild fluctuations in the magnetospheric fields. In response to these fluctuations, in accordance with Lenz's Law, massive currents flow throughout the magnetosphere. It is these high altitude currents that induce voltages at ground level. If the magnetic field of the solar wind is in the same direction as the Earth's field, then magnetic reconnection does not occur and the magnetosphere is much more separated and protected from the solar wind. Under these conditions, the effects of solar mass ejections are much less significant. In order to know what is going to happen on Earth we must know not only what happened on the Sun but also the nature of the magnetic fields that are carried along with the solar wind. This is one reason why the DSCOVR satellite is so essential to space weather forecasters; to determine the nature of the solar wind before it arrives. While space weather forecasting remains a very difficult endeavour, satellites such as DSCOVR, SOHO, and GOES have made collection of data more accurate and timely; thereby increasing forecasting accuracy of major space weather events.

The NOAA Space Wether Prediction Center (SWPC) in Boulder is nation's official source for space weather alerts and warnings; and is one of the world centers that makes forecasts of solar and geomagnetic activity. Each day forecasts out at least three days are issued for the likelihood of solar flares and intensity, proton events, x-ray flux, and geomagnetic storms. These forecasts are used by a multitude of customers across the nation and around the world whom are concerned with a variety of space weather vulnerable systems, communications, navigation, or health. SWPC is a worldwide nerve center for thousands of data streams, including x-ray and particle flux data from the GOES satellites, Hα images and magnetograms from observatories around the world, measurements of the geomagnetic field at many locations, and 10.7-cm radio levels from several radio telescopes. Each day the features of the solar disk are analyzed and mapped so that the evolution of active regions, coronal holes, filaments, and neutral lines may be carefully studied. Forecasters consider all of this information when making their forecasts, even so, the science of solar physics, the magnetosphere, and the interplanetary medium are still not well understood. Many partial mathematical models have been developed, but there is no total comprehensive model of the Solar-Terrestrial environment; although a few advancements in heliophysics have resulted in some new forecast models of prediction.

In most cases, the ability to predict the behavior of nature comes from a mathematical model. For example, the motion of an object falling in a gravitational field can be modelled using the mathematical expression $v = g \times t$. Earth weather forecasters have been trying for the last 30 years to construct a mathematical model of the global weather using the very complex equations of fluid dynamics to describe the circulation of the oceans and atmosphere. Even with the best supercomputers to run these models, it has proven impossible to precisely model Earth weather. Modelling the solar-terrestrial environment is vastly more complex. The physics necessary to do this includes not only fluid dynamics but also Maxwell’s equations. This combination is known as ***magnetohydrodynamics*** (MHD), and at the present time the equations of MHD cannot be completely solved analytically. Numerical solutions exist which involve the use of a computer in a “trial and error” fashion. Numerical solutions, however, can give incorrect results and at best are an approximation. There is some suspicion that we have not yet developed the physics necessary to fully understand the Sun, where strong magnetic fields are erupting and plasmas swirl at ultra-high temperatures. Certainly it is impossible to simulate these conditions in experiments on Earth.

Research to improve solar forecasting is occurring in two major areas. The first area is the correlation of observable phenomena with effects on Earth. For example, we have observed a strong correlation between sunspot cycles and disturbances on Earth. However, this correlation is very coarse; we know that during a certain period of years there will be high levels of solar activity and the accompanying disturbances on Earth. But we cannot accurately predict these disturbances as happening over specific days or hours, as we would like to be able to. Many researchers are trying to refine the correlations between observable symptoms, like increased radio emission, and subsequent eruptions of mass. Some of the best correlations yet are those that have been found between the evolution of sunspot groups and eruptions.

The second area of work is that of constructing a model for the Solar-Terrestrial environment. In addition to the complexities of MHD, the problem is difficult because there are three different domains involved, which all couple together. The first domain is that of the Sun; to simply construct a mathematical model of the Sun is far beyond us at the present time. There are still many mysteries about what is going on inside the Sun, what triggers flares and even why sunspots form. The second domain is the interplanetary medium, once thought of as empty space. This space is filled with the solar wind plasma, which is not fully understood. The third domain is the geomagnetosphere, with its many regions and currents. The magnetotail, extending for millions of kilometers out from Earth, has been difficult to study directly and remains poorly understood. Another complication is that these three domains are not at all separate. A change in one of these domains can have major consequences on the surface of Earth; we hope one day to have a comprehensive model for the entire solar-terrestrial environment but this is certainly a problem for physicists of the future.

Despite these difficulties, some advances in non-comprehensive modeling have occurred, to include development of a large-scale, physics-based heliospheric prediction tool known as the WSA-Enlil model. This model can help provide 1 to 4 days advance notice of solar wind speed and density changes, and when submitted by forecasters to include calculated parameters of CME analysis, aids tremendously in determination of whether a CME may be Earth-directed, and if so, provide timing solutions. Another model, known as the geospace model, provides short-term guidance of the Earth's magnetospheric state using real-time solar wind data and 10.7cm solar flux as inputs to provide a 15 to 45 minute forecast of the possible state of the geomagnetosphere. This model provides another tool to help make decisions regarding the overall planetary geomagnetic response state - perhaps assisting forecasters with warning issuance decisions.

Forecasters will continue to make space weather forecasts based on our present knowledge of the Sun and the Earth's magnetosphere, using all available observation data and model prediction tools as sources for their decision-making. Forecasting accuracy will continue to improve as additional advances in heliosphereic science continues and more reliable models come into operation. The physics of the solar-terresrtial environment is still one of the great frontiers; awating new generations of scientists, more modeling advances, and greater understanding of solar physics.

Problems and Questions

1. Estimate the radius of curvature of the path of a solar wind proton when it encounters the geomagnetic field. Assume that the proton is moving perpendicular to the field at 400 km/s and the field has a strength of about 10^{-7} tesla). What is the motion of the proton like if there is a component of velocity along the field lines?
2. Explain the processes by which solar activity can lead to induced currents in conductors on Earth.
3. What is magnetic reconnection and why is it significant in how the Sun can affect Earth?
4. How are low-orbiting Earth satellites affected by solar disturbances? What about high-orbiting satellites?
5. What is magnetohydrodynamics and how is it used to help us understand the solar-terrestrial environment?

Answers to Chapter Questions

Chapter 1

1. (a). It is estimated that there are 10^{11} stars in our galaxy. This can be estimated by assuming that the solar system is in a circular orbit around the center of the galaxy. Using R = 30,000 light-years and T = 200,000,000 years, Newton's Law of Gravitation can be applied ($G = 6.67259 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$):

$$\frac{GM_{galaxy}M_{ss}}{R^2} = \frac{4\pi^2 M_{ss}R}{T^2} \to M_{galaxy} = \frac{4\pi^2 R^3}{GT^2}$$

This gives, for M_{galaxy} is 3.4×10^{41} kg, and using 10^{30} as a typical star mass gives 3.4×10^{11} as the number of stars in the galaxy.

(b). From the estimated size of the Universe (radius of 15 billion light-years) and distribution of galaxies, it is estimated that there are about 10^{11} galaxies in the Universe.

(c). $10^{11}s \times \frac{1y}{365.24d} \times \frac{1d}{86400s}\ s \cong 3169\ years\ \ or\ \ about\ \ 3,000\ years$

(d). $10^{11}\ stars/galaxy \times 10^{11}\ galaxies/universe \approx 10^{22}\ stars/universe$

(e). $10^{22}\ stars/universe \times 10^{30}\ kg/star \approx 10^{52}\ kg/universe$
This is the mass of the visible stars. It is now believed that there must be a large amount of mass we can't see in the form of "dark matter."

2. Just as an "Earth-year" is the time for Earth to travel around the Sun (the period of revolution of the Earth), a Sun-year is the time for the Sun to travel once around the center of the galaxy. This time is estimated to be 200,000,000 years.

(a). This occurs when the Sun is about 10 billion years old.

$$10\ billion\ yrs \times \frac{1\ Sun\text{-}year}{.2\ billion\ yrs} = 50\ Sun\text{-}years\ old$$

(b). About the same age. It remains a red giant for about 250 million years or 1.25 Sun-years.

(c). $15\ billion\ yrs \times \frac{1\ Sun\text{-}year}{.2\ billion\ yrs} = 75\ Sun\text{-}years\ old$

3. Time could be added as another axis, in the third dimension (out of this page), like a z-axis.

4. Conservation of Angular Momentum: Iw = I'w'

$$since\ I = \frac{2}{5}MR^2\ \ (for\ a\ sphere)$$

$$\text{and}\ w = \frac{2\pi}{T}\quad : \left(\frac{2}{5}MR^2\right)\left(\frac{2\pi}{T}\right) = \left(\frac{2}{5}MR'^2\right)\left(\frac{2\pi}{T'}\right)$$

$$\frac{R^2}{T} = \frac{R'^2}{T'} \to T' = \left(\frac{R'}{R}\right)^2 T$$

$$using\ R' = \frac{6.95 \times 10^{8}\ m}{1.49 \times 10^{11}\ m/AU} = 4.66 \times 10^{-3}\ AU$$

$$T' = \left(\frac{4.66 \times 10^{-3}\ AU}{5\ AU}\right)^{2}(12\ y) = 1.04 \times 10^{-5}\ y \times 365\ d/y = 3.80 \times 10^{-3}\ days$$

$$= 5.5\ minutes$$

5. (a). The Sun contains all of the first 92 elements, but by far the most abundant are Hydrogen (92%) and Helium (7.8%).

   (b). Helium and carbon can be produced by fusion inside a star the size of the Sun.

   (c). For larger stars, elements in the periodic table up to Iron (#26) can be produced.

   (d). Elements 27 to 92 are formed in the Super Nova process.

6. Ideas, models, and calculations of how a star ends its life are still evolving, and so some of the specifics may undergo change in the future. Generally, if a star has about the mass of the sun, it goes through a red giant stage and then eventually becomes a white dwarf. A white dwarf has a mass about the Sun's mass or greater, but a size only as big as Earth, and eventually cools down to become a cold, black dwarf.

   More massive stars may lose some of their mass during their lifetime. Their final mass determines what becomes of the stars. Mass losses during the life of a star are poorly known, but it is now thought that stars with initial masses up to 6 or 8 solar masses can end up as white dwarfs. Stars whose final mass is greater than 1.4 solar masses (the Chandrasekhr limit) cannot end up as white dwarfs. Stars that initially have between 8 and 20 solar masses end up as neutron stats, many of them shedding mass by becoming supernovas. Stars with initial masses more than 20 solar masses are also thought to form neutron stars in an intermediate stage, but if the neutron star mass is greater than some limit (not known exactly, but probably between 1.6 and 2.4 solar masses), a new stellar collapse occurs and nothing can stop it—there is no form of pressure that can counteract gravity and an unlimited collapse continues. The core becomes a black hole in less than one thousandth of a second.

Chapter 2

1. Sun-Earth distance $= 1.5 \times 10^{8}\ km = 1.5 \times 10^{11}\ m$

$$use\ v = \frac{\Delta x}{\Delta t} \rightarrow t = \frac{x}{v}$$

   (a). $t = \dfrac{1.5 \times 10^{11}\ m}{3.0 \times 10^{8}\ m/s} = 500\ s = 8\,\text{min}\ 20\ s$

   (b). Same as (a) since $V_{\text{x-rays}} = 3.0 \times 10^{8}\ m/s$

   (c). 400 *km/s* = $4 \times 10^{5}\ m/s \rightarrow t = \dfrac{x}{v} = \dfrac{1.5 \times 10^{11}}{4.0 \times 10^{5}} = 3.75 \times 10^{5}\ s \approx 4.34\ days$

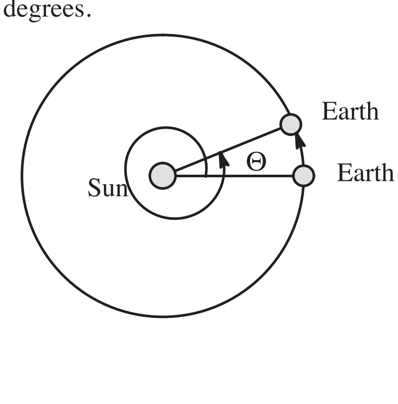
   (d). 500 *mi/hr* = 223 *m/s* $\rightarrow t = \dfrac{1.5 \times 10^{11}}{2.23 \times 10^{2}} = 6.71 \times 10^{8}\ s \approx 21.3\ y$

2. $v = \dfrac{2\pi R}{T}$ from circular motion

R = 6.95 $\times$ 10 ^{8} m , T = 26.8 days = 2.32 $\times$ 10^{6} s

$$v = \frac{(6.28)(6.95 \times 10^{8}\ m)}{(2.32 \times 10^{6}\ s)} = 1.88 \times 10^{3}\ m/s$$

3. (a). 8000 K (b). 4300 to 50,000 K (c). about 10^{6} K
4. (a). About 10^{-6} kg/m^{3} (b) $\sim$10^{-4} kg/m^{3} (c). 10^{-17} kg/m^{3}
5. .7% of total mass disappears, or 0.007 $\times$ mass of He^{4}.
   He^{4} has mass of 4 atomic units or 4 $\times$ m_p = 4 $\times$ 1.67 $\times$ 10 $^{-27}$ *kg per atom*
   Mass that disappears = (0.007)(6.68 $\times$ 10^{-27}) = 4.68 $\times$ 10^{-25} *kg*
   Energy that appears = E=mc^{2} = (4.68 $\times$ 10^{-25})(3.0 $\times$ 10^{8})^{2} = 4.20 $\times$ 10^{-8} *joules per reaction*
   $$\frac{10^{26}\ J/s}{4.21 \times 10^{-8}\ J/reaction} = 2.38 \times 10^{33}\ reactions/s$$
6. 5 $\times$ 10^{6} *tons/s* $\times$ 907 *kg/ton* = 4.536 $\times$ 10^{9} *kg/s*
   $$\frac{1.99 \times 10^{30}\ kg}{4.55 \times 10^{9}\ kg/s} = 4.39 \times 10^{20}\ s = 1.39 \times 10^{13}\ yrs$$
   About 10,000 times longer than the age of the Earth!
7. $E_k = \frac{3}{2}k_B T = \frac{1}{2}mv^2$
   $$v = \sqrt{\frac{3k_B T}{m}} = \sqrt{\frac{3\ (1.38 \times 10^{-23})(1.5 \times 10^{7})}{1.67 \times 10^{-27}}} = 6.1 \times 10^{5}\ m/s$$
8. $$P = K_B T\left(\frac{N}{v}\right) \rightarrow \left(\frac{N}{v}\right) = \frac{P}{K_B T} = \frac{1.01 \times 10^{5}\frac{N}{m^2}}{(1.38 \times 10^{-23})(293)} \qquad \frac{(1\ atmosphere,\ sea\ level)}{(room\ temperature)}$$
   NOTE: for Boulder, CO, use 0.83 instead of 1.01 in the above equation.
   (a) $\left(\frac{N}{v}\right) = 2.5 \times 10^{15}\ \frac{particles}{m^3}$
   (b) Assuming that the particles are protons with m = 1.67 $\times$ 10^{-27} kg:
   $$10^{-6}\frac{kg}{m^3} \times \frac{1\ particle}{1.67 \times 10^{-27}\ kg} = 5.99 \times 10^{23}\ \frac{particles}{m^3}$$
   (c) Assuming a density of $2 \times 10^{9}\frac{kg}{m^3} \times \frac{1\ particle}{1.67 \times 10^{-27}\ kg}$
   $$= 1.2 \times 10^{27}\ \frac{particles}{m^3}$$
9. Synodic rotation period is seen from Earth. Relative to the stars, the Sun had actually "over-rotated" by Θ degrees.



$$\Theta = \frac{28\ days}{365\ days} \times 360^{o} = 27.6^{o}$$

or Sun has actually rotated

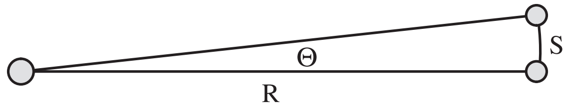
$$360^{o} + 27.6^{o} = 387.6^{o}$$

Sidereal Period will be

$$\frac{360^{o}}{387.6^{o}} \times 28\ days = (93\%) \times 28\ days = 26\ days$$

Chapter 3

1. Angular size = $\Theta = \dfrac{S}{R}$



$$\Theta_{Moon} = \frac{Diameter}{Earth\text{-}Moon\ distance} = \frac{3.48 \times 10^6\ m}{3.8 \times 10^8\ m} = 9.16 \times 10^{-3}\ rad \times \frac{360^o}{2\pi\ rad} = 0.525^o$$

$$\Theta_{Sun} = \frac{Diameter}{Earth\text{-}Sundistance} = \frac{1.39 \times 10^9\ m}{1.5 \times 10^{11}\ m} = 9.27 \times 10^{-3}\ rad = 0.531^o$$

The angular sizes are nearly identical so the Moon almost exactly covers the disk of the Sun during a total eclipse. This reveals the reddish chromosphere which lies just outside the bright disk of the photosphere.

2. (a). White light is a mixture of nearly all the visible wavelengths. The visible wavelengths arise from energy level transitions in atoms at temperatures of about 6000 K, which is typical of the photosphere and low chromosphere.

   (b). The Hα wavelength of 656 nm results when Hydrogen atoms make the transition from the 2nd excited state to the first excited state, emitting a 1.9 *eV* photon. This occurs at temperatures of about 4000 K found in the low chromosphere.

   (c). Ultraviolet light (UV) originates in the high chromosphere at temperatures of about 70,000 K. This UV results from transition in atoms.

   (d). X-rays are largely the result of plasma rapidly decelerating as it slams into denser material. This occurs when plasma from flares returns and collides with the denser chromosphere. These are known as Bremsstrahlurg x-rays.

   (d) and (e). Radio and microwaves (really the same) are generated when charges are driven into circular motion as they wrap around magnetic field lines. This happens during flares. Radiation from charges in circular motion is known as synchrotron radiation.

3. The Zeemann effect is the splitting of emission lines which occurs when the emitting atom is in a magnetic field. By studying the Zeemann effect on light from the Sun, we can estimate the strength of the field at the place on the Sun where the light originates. Magnetograms (or magnetic maps) are constructed in this way.

4. In white light the sunspots appear clearly but no other features are apparent. In Hα many other features appear. The most important of these are filaments. In the x-rays, coronal holes and other evidence of coronal activity can be seen.

5. The energy levels in eV of hydrogen can be found from $E_n = 13.6 - \dfrac{13.6}{n^2} = 13.6\left(1 - \dfrac{1}{n^2}\right)$
   n = 1 gives 0 (the ground state); n = 2 gives 10.20 *eV* and n=3 gives 12.09 *eV*. The transition from the n = 3 to the n = 2 energy level produces a photon of energy 12.09 – 10.20 = 1.89 *eV*. The wavelength of this photon is given by $\lambda = \dfrac{hc}{E}$.
   A convenient form of this is $\lambda = \dfrac{1240\ eV \cdot nm}{E} = \dfrac{1240\ eV \cdot nm}{1.89\ eV} = 656\ nm$

6. See section 3.2
7. See section 3.2 and Figure 3–4.
8. See section 3.3 and Figure 3–5.
9. See section 3.3

10. See section 3.4

11. See section 3.5

12. Similar to problem 1 (a), Chapter 1
Using the Law of Gravitation and the centripetal force equation:

$$F = \frac{GM_{earth}m_{satellite}}{R^2} = \frac{4\pi^2 m_{satellite}R}{T^2}$$

solving for R (orbit size): $$R = \left[\frac{GM_{earth}T^2}{4\pi^2}\right]^{1/3}$$

$$= \left[\frac{(6.67 \times 10^{-11}\ m^3kg^{-1}s^{-2})(5.98 \times 10^{24}\ kg)(8.64 \times 10^4\ s)^2}{4\pi^2}\right]^{1/3} = 4.22 \times 10^7\ m$$

In Earth radii: $$\frac{4.22 \times 10^7\ m}{6.38 \times 10^6\ m/radius} = 6.62\ radii$$

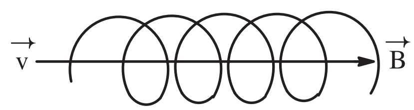
13. A black body absorbs all radiation falling on it. No light reflects, hence it is black. By Kirchhoff's law, a body which completely absorbs all wavelengths emits all wavelengths. So we have come to speak of "black body radiation" as that radiation which has all wavelengths in accord with Planck's law.

Chapter 4

1. $$F = qvB = \frac{mv^2}{R} \qquad v = 400\frac{km}{s} = 4 \times 10^5\frac{m}{s}$$

$$R = \frac{mv}{qB} = \frac{(1.67 \times 10^{-27})(4 \times 10^{5})}{(1.6 \times 10^{-19})(1 \times 10^{-7})} = 41,750\ m\ or\ 41.8km$$

With a component of velocity along $\vec{B}$ field lines, the motion will be corkscrew-like:



2. Fluctuations in the solar wind cause large voltages to be induced in the magnetosphere. Part of this EMF causes currents to flow along magnetic field lines between the magnetosphere and ionosphere. As solar wind intensity changes, so does the strength of this current. This varying current has its own magnetic field which combines with Earth's field to produce a changing magnetic field of the surface of the Earth. Such a changing field induces currents in any conductors, such as power lines or pipe lines.

3. Magnetic reconnection is the joining of the Sun's and the Earth's magnetic fields, and occurs most readily when the two fields are antiparallel. When the fields are joined, solar wind material can more readily enter the magnetosphere, enhancing the energy input to the magnetosphere.

4. Low-orbiting satellites can be engulfed in the Earth's atmosphere as it expands due heating from increased radiation levels from the Sun. This encounter with the atmosphere causes a frictional drag on satellites, which causes them to drop in their orbits, and possibly fall to Earth prematurely. High-orbiting satellites are often exposed to energetic particles during intervals of high solar activity. These particles can cause damaging charge buildups, degrading solar panel output and can destroy or damage microelectronic devices.

5. Magnetohydrodynamics (MHD) is a study which combines features of fluid dynamics and Maxwell's Equations. It is hoped that MHD can provide a model which can be used to predict solar activity and its resulting effects on Earth.

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Activity 1

Building a Spectroscope

Reading

Chapter 3, sections 1 and 2 and Chapter 4, section 1

Purpose

To build and use a spectroscope as an instrument to study the chemical properties of reflected or emitted light.

Materials

Simple Spectroscope:

old shoe box, 6 cm square of aluminum foil
tape
2 cm square of diffraction grating (holographic grating is the best)
scissors or a razor knife

Option: Quantitative Spectroscope

all of the above
a piece of graph paper about 3 cm x 10 cm with a small grid (1 mm square)

Option: Semi-Permanent Quantitative Spectroscope

all the supplies from Quantitative Spectroscope

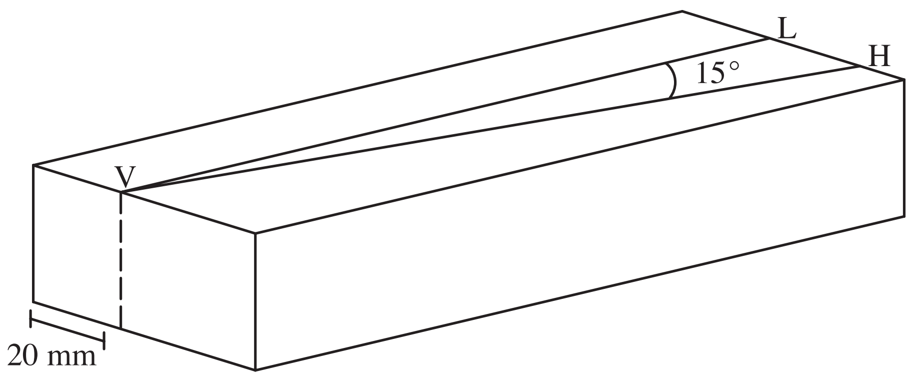
substitute a more substantial box for the shoe box. This could be made from 1/8" masonite, heavy cardboard, plastic, plywood, or even sheet metal, depending on the skills and equipment of the builder.

substitute 2 razor blades for the foil or use two sheets of aluminum cut from a soda can such that each is about razor blade sized with 1 straight edge.

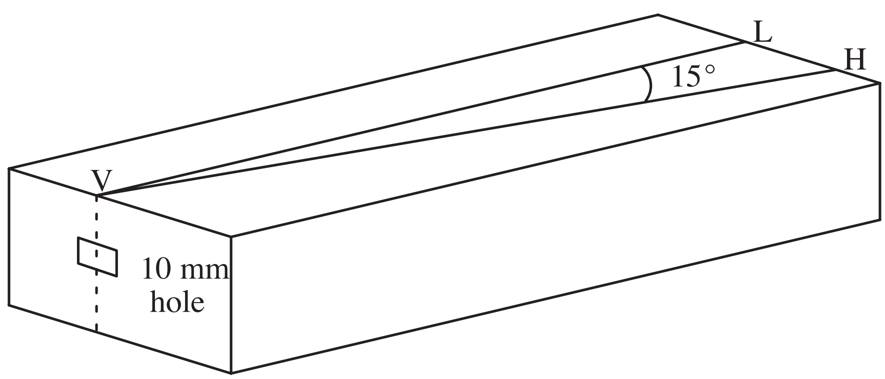
Option: Spectroscope kits can be purchased and assembled quickly.

Procedure

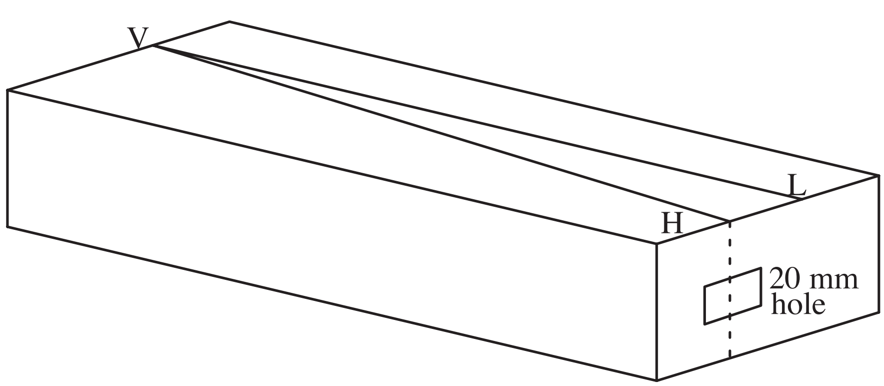
1. On the bottom of the shoe box lay out a 15° angle with the vertex about 20 mm in from one side as shown:



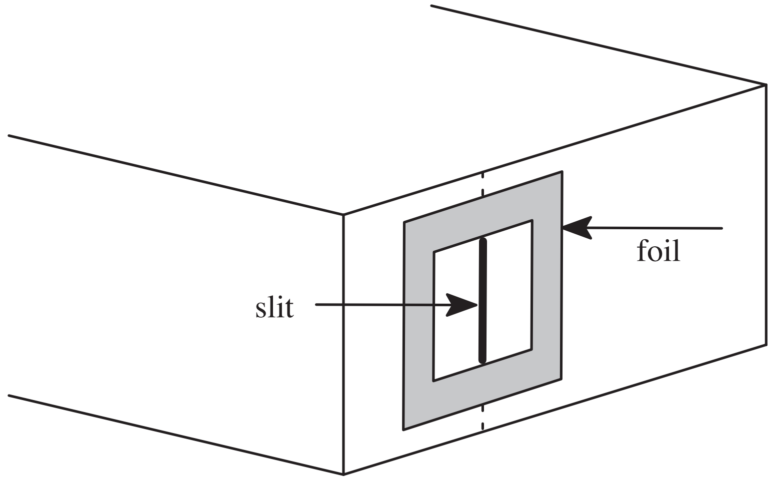
2. On the vertex end of the box cut a 10 mm square hole through the box, centered above the vertex (V) you drew and center in the end as shown:



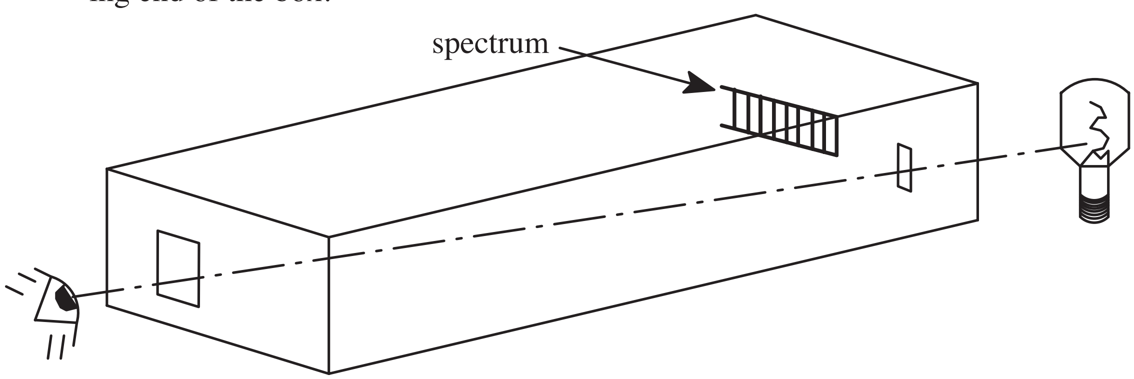
3. At the other end of the box cut a 20 mm square hole centered above the hypotenuse line (H) you drew on the box.



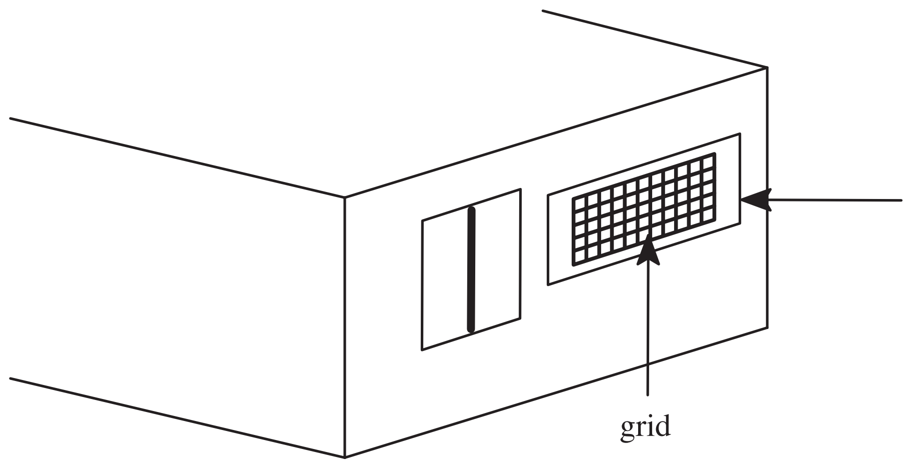
4. Center the foil over the 20 mm hole and tape it into place. Cut a vertical slit in the center of the foil, just filling the hole. Try to keep the slit very narrow—0.5 mm or less.



5. Put a small piece of tape on one edge of the grating—be careful not to get your fingers on the grating, handle it by the edges only.
6. Temporarily tape the grating over the vertex hole on the inside of the box. Set the square of the grating square with the hole.
7. Put the lid on the box, line up the slit with a light source as you look through the grating end of the box.



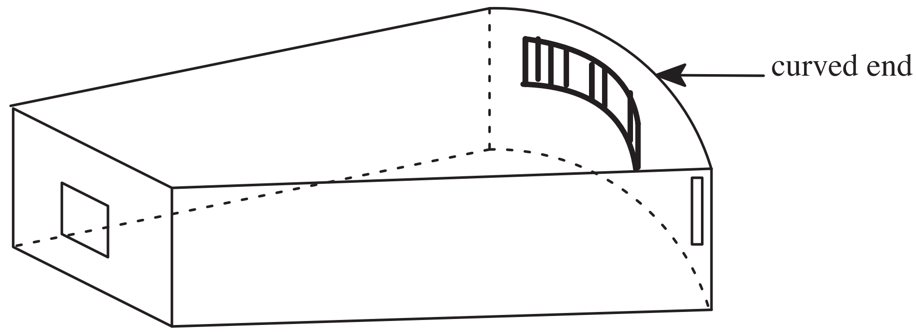
8. A spectrum of colors should appear on the inside of the box to the side of the slit.
9. If the spectrum doesn't appear, rotate the grating 90° and try again. When the grating is finally oriented so that the spectrum is parallel to the slit, tape the other 3 corners of the grating in place.
10. To make this a quantitative device, *ie*. to be able to make measurements on the spectra, a grid needs to be added to the system and then calibrated.
    With the box in use, note the position of the spectrum inside the box. If possible, put a pencil mark around the region occupied by the spectrum.
11. Cut out the region that you marked and center the piece of graph paper over the opening, taping it in place on the outside of the box.



12. Using a florescent light, carefully mark the position of the prominent green and purple lines (others can be used but you'll need to look up their wavelengths). The green line has a wavelength of 546 nm and the purple line a wavelength of 436 nm.
13. Count the grid lines between the marks and scale the grid accordingly. Put convenient numbers on the grid so that values can be read from the grid directly as the spectroscope is used.
14. After building the shoe box type of spectroscope, modify it to: have an adjustable slit, a more accurate grid, a more rugged box.
15. A better slit can be obtained by using 2 double-edged razor blades, or by using 2 pieces of aluminum cut from an aluminum beverage can (both the razor blades and the aluminum pieces are very sharp!). Use a note card, another razor blade, or another aluminum strip as a spacer for the slit.
16. A much better box than a shoe box could be made to house your spectroscope. Cigar boxes are OK but may be too small, and they're certainly hard to cut.
    If you plan to use masonite, plywood, etc. make sure that you lay out the box around the best geometry of the shoe box design. If 15° is not the best angle, change it. Remember the box design is best determined by the slit-grating-grid configuration and not by the size of the box.
17. The actual math relationship of spectral lines and box geometry is not linear, and therefore it loses accuracy the farther away from the calibration lines you make readings. If possible, use a larger number of known lines from Geissler tubes, or other gas discharge tubes and derive the scale formula required. Another method is to change the geometry of the box (a better method is to curve the grid-slit arrangement as shown below.

Using the spectroscope:

1. Make observations of a number of different light sources and use colored pencils to draw what you see as accurately as possible (a florescent light, a "black" light, the sun (be careful here), "grow lights," clouds, neon signs, etc.). You should note that



some light sources don't show a full spectrum but may show only a collection of colored lines or bands. The spectrum of the sun should show a number of black lines on the full rainbow of colors. Do not point your spectroscope directly at the sun. Record what you see and account for the differences.

2. If your spectroscope is a quantitative kind, determine the numerical position of the specific lines and bands. Try to correlate the numerical values with known values for given elements. Some of these are listed in the table that follows. With the black lines in the solar spectrum, try to identify the specific Fraunhofer lines that you can see, and then correlate them to values given for elements in the sun. Why are these lines black?
3. If a set of Geissler tubes or gas discharge tubes is available (neon signs and florescent tubes are gas discharge tubes), make a reference set of line values for specific elements. Try to carefully measure the lines from hydrogen, mercury, helium, and water vapor if these tubes can be obtained.
4. Try placing colored filters between the light source and the slit. Expensive glass filters used for photography, or gels used in theater lights are excellent, but again, costly. Simple colored cellophane from art supply stores or even packages can be used. Or try food coloring in a glass between the light and the slit to make your own colored filter. Explain how these filters can help or hinder your analysis (see Activity 5).
5. Light from burning sources can be analyzed also but can be hard if it's difficult to keep the material burning or if the burning by-products are dangerous. Try burning salt, sugar, salt substitutes, Rolaids®, etc. by using a Bunsen burner or a propane torch. Hold small amounts of material on a small wire loop held in the flame. Do any of these lines match any lines in the solar spectrum?
6. Set up a camera at the grating end of your spectroscope and try to photograph some of the spectra you produce. This is a good exercise in optics. Is it possible to photograph your spectrum of the sun and capture the black Fraunhofer lines?

Table of Solar Absorption Lines

(from the CRC handbook)

Line Name	Due To	Wavelength (nm)
M	Fe	372.8
L	Fe	382.0
K	Ca	393.4
H	Ca	396.8
h	H	410.2
g	Ca	422.7
G	Fe Ca	430.8 430.8
G'	H	434.0
F	H	486.1
b_4	Fe Mg	516.8 516.7
b_2	Mg	517.3
b_1	Mg	518.4
E_2	Fe	527.0
D_2	Na	589.0
D_1	Na	590.0
C	H	656.3
B	O O	759.4 762.1

Activity 2

Energy Transport in the Sun

Purpose

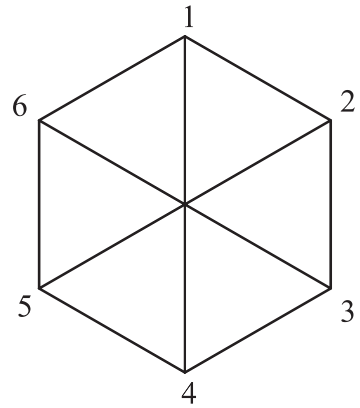
This is a 2-D demonstration of how a photon—a small bundle of light energy—might move in its journey from the interior to the surface of the Sun. Creative teachers might modify this into a game for several players that includes questions about the Sun as levels are reached, etc. Be imaginative!

Materials

1 six-sided die
1 pencil
1 sheet of isometric graph paper (example given in this section)
1 piece of corrugated cardboard the size of the graph paper
1 straight pin
1 drawing compass

Procedures

1. Find the center of the isometric graph paper (marked with an "O") and call it the center of the Sun.
2. Note that 6 lines radiate from this point to 6 new points, and so on, over the page.
3. To make keeping track a little easier, draw a series of circles at every 2 or 3 intersection points out to the twelfth circle. Call the outer circle the solar surface.
4. Assign the directions of the six lines radiating from a point to the values 1–6 as shown. The values can be in any arrangement you choose, but must be used consistently throughout this entire exercise.



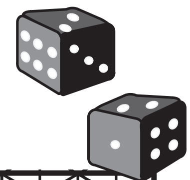
An example of numbering the directions of the hexagon.

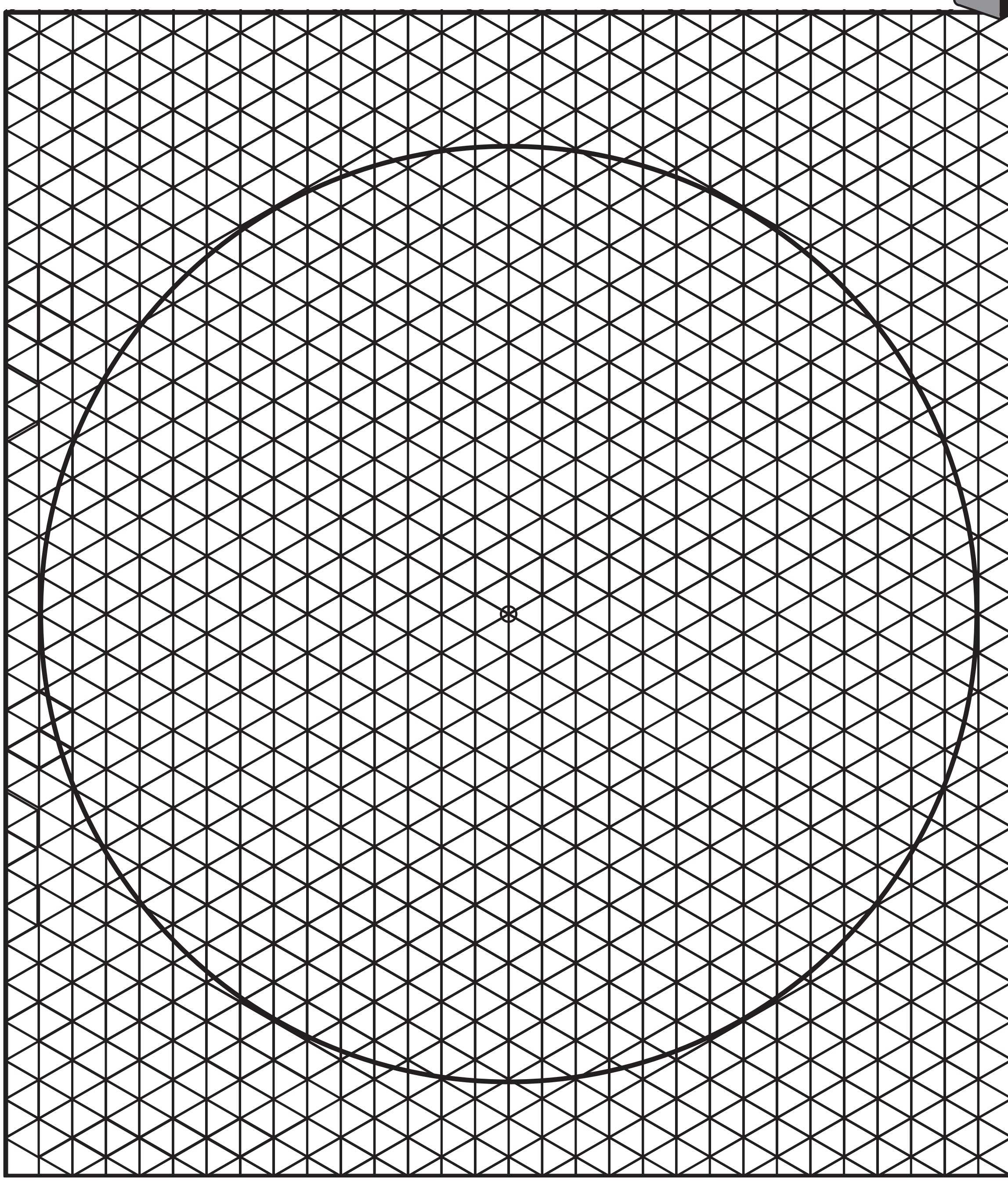
5. Starting at the center, roll the die and move 1 unit in the direction indicated. From this new point roll again and move 1 unit in the direction indicated. Continue until the surface of the sun is reached. Keep track of the total number of rolls needed to reach the edge of the sun.
6. Computer-oriented students may want to write a computer program to simulate the photon's movement. Use the random number generator to generate values 1–6 to simulate rolls of the die, and a matrix or array to keep track of position. A graphics display could also be incorporated into the program.
7. Have a group of students (class) each do this exercise and tabulate the average number of trials it takes to reach each radius. Then compare the averages with the value of the radius squared, i.e. at r=4, compare trials to 16.
8. A game idea might be as follows:
   a. 3 or 4 students start with a pin at "O"
   b. Each takes turns rolling the die and moving the pin to a new location
   c. At each even radius line, (2, 4, 6...), a question card is drawn from a deck of index cards, prepared by the teacher or class with questions about the sun).
   d. If the question is answered correctly, the student can take a "quantum leap" to an odd radius (3, 5, 7...).
   e. If they answer incorrectly, a turn is lost.
   f. The winner is the first to reach the solar surface. Give each winner a package of sunflower seeds or a pack of Starburst® candy.
9. Based on the game idea above, try different grid arrangements to match the different dice available at hobby and game stores (especially "Dungeons and Dragons™" games).

   Draw from different question decks based on odd or even rolls. For older students, one deck might be for calculation problems, the other for verbal questions.

Photons take a collision-filled journey to the surface of the Sun. The gamma photons are absorbed and re-emitted repeatedly in the radiative core of the Sun. The energy produced in the core may take as long as 50 million years to work its way out!

See if you can work your way out using the dice to decide your path.





For the Teacher

The mathematics that describes the photons' movement that carries the energy from the solar interior to the surface is based on probability and statistics. Even though the exercise described is 2-D, the actual case of 3-D photon movement in the sun follows the same mathematical theory and can be shown to produce the same result.

To show how the process works, a 1-D model will be described. Examine a line with the starting point at 0 and each jump, either backward or forward, is called j (+j or –j). After a lage number of jumps, n, the average distance X_n should be zero,

or

$$\frac{\sum X_n}{n} = 0$$

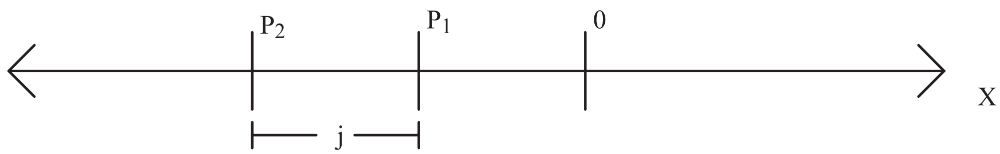
The standard deviation,

$$\sigma$$

where

$$\sigma_n^2 = \frac{\sum X_n^2}{n}$$

will give the statistical position of the photon from 0 after n jumps.



Then if at (n–1) jumps, the point P_1 is the location of the photon, P_2 is the location after one more jump j.

The distance is then given by:

$$X_n = X_{n-1} \pm j.$$

Thus:

$$\sigma_n^2 = \frac{\sum X_n^2}{n} = \frac{\sum X_{n-1}^2}{n} \pm \frac{2 \times j \times \sum X_{n-1}}{n} + \frac{n \times j^2}{n}$$

But,

$$\frac{\sum X_{n-1}}{n} = 0$$

Therefore:

$$\sigma_n^2 = \sigma_{n-1}^2 + j^2$$

This is a recursion formula such that

$$\sigma_{n-1}^2 = \sigma_{n-2}^2 + j^2$$

Then :

$$\sigma_n^2 = \sigma_{n-2}^2 + 2 \times j^2 = \sigma_1^2 + (n-1) \times j^2$$

However,

$$\sigma_1^2 = j^2$$

Therefore:

$$\sigma_n^2 = n \times j^2$$

This is the squared relationship that you should see in the average number of rolls to each radius.

It has been determined that for the sun, each photon jump is about 1cm and the radius of the sun is about

$$7 \times 10^{10}\ cm$$

So,

$$\sigma_n = 7 \times 10^{10}\ cm \quad \textit{for 1 photon to reach the surface}$$

Substituting these values in

$$\sigma_n^2 = n \times j^2$$

gives

$$\left(7 \times 10^{10}\right)^2 = n \times 1^2$$

$$n = 5 \times 10^{21}\ jumps$$

The speed of light is

$$3 \times 10^8\ \frac{m}{s}$$

and assuming little or no time for the photon to wait at each jump point, then

$$5 \times 10^{21}\ jumps \times \frac{.01\ m}{1\ jump} \times \frac{1\ s}{3 \times 10^8\ m} = \frac{5}{3} \times 10^{11}\ seconds$$

for the photon to reach the sun's surface.

Converting this to years:

$$\frac{5}{3} \times 10^{11}\ seconds \times \frac{1\ h}{3600\ s} \times \frac{1\ d}{24\ h} \times \frac{1\ y}{365\ d} = 5300\ years$$

Even though this is a very long time for 1 photon, the process of being absorbed and remitted at each jump adds considerable time to the process—up to 50 million years.

Activity 3

Measuring the Solar Constant

Purpose

With this activity, we will let solar radiation raise the temperature of a measured quantity of water From the observation of how much time is required for the temperature change, we can calculate the amount of energy absorbed by the water and then relate this to the energy output of the Sun.

Materials

Simple Jar and Thermometer

small, flat sided glass bottle with 200 ml capacity—the more regular the shape the easier it will be to calculate the surface area later

cork stopper for the bottle with a hole drilled in it to accept a thermometer; the regular cap of the bottle can be used, but the hole for the thermometer may have to be sealed with silicon or caulking after the thermometer is placed in it.

thermometer with a range up to at least 50 °C

stopwatch

black, water soluble ink

metric measuring cup

Option: Insulated Collector Jar and Digital Multi-Meter (DMM) Temperature Probes

all of the above but substitute the temperature probes from a DMM or a computer to collect the data; the computer could also provide a more accurate time base

a more sophisticated, insulated collector bottle could be made—try to minimize heat loss to the environment with your design.

substitute different materials other than water as the solar collection material. Ethylene glycol (antifreeze) might be used, or even a photovoltaic cell could act as a collector. Remember, some of the parameters in your calculations will need to be changed if water is not used

different colors of water soluble ink

Procedures

1. Try to do the data collection as close to noon as possible on a clear, cloudless day.

2. Prepare the collector bottle with 150 ml of water with a few drops of the ink to make it fairly black.
3. Insert the cork/thermometer and let the temperature stabilize to a mean air temperature by placing the collector in the shade for 20–30 min or until a check every 2–3 min shows no temperature change.
4. Shade the collector as you move the unit into the sun and set it so that the flat surface is as perpendicular to the incoming solar radiation as possible.
5. As you unshade the collector, begin recording the time and the temperature. (See data sheet)
6. Allow the collector to absorb the sun's rays for about 20 min or at least enough time to get a 3–4 °C temperature rise. Record the elapsed time and temperature rise.
7. Cool the unit by placing it under running water and repeat the procedure two more times so that you have three total sets of data.
8. Measure the size of the bottle's surface that is exposed to the sun and express the area in square meters. This might be tough with odd shaped bottles.

Related Activities:

1. Students are always impressed with the heat that can be generated when the sun's energy is concentrated. Most have used simple hand lenses and magnifiers to do this but there are other interesting ways to accomplish the same thing.
2. Sheet magnifiers (a form of Fresnel lens) of various sizes can concentrate enough heat that small jewelry items can be enameled, soldered, or brazed.
3. With a class of students, have them each obtain a small plane mirror. Use one from a make-up compact, or, better yet, a 100 mm $\times$ 150 mm mirror that students put inside their lockers. Have the students gather outdoors on a sunny day and arrange themselves in a semi-circle facing the sun. Place a target such as a crumpled up sheet of paper out in front of the students and have them shine their reflection of the sun onto the paper. A thermocouple style temperature sensor could also be used to investigate the concentrated energy. The paper will ignite with the collective energy.
4. A great cold weather activity is to have students form lenses from ice. Lenses without air bubbles and other flaws are not easy to make but slightly flawed ice can still get the idea across. A 100-mm ice lens can set paper on fire. Some people have made ice lenses very carefully and then been able to use them in cameras and telescopes. (Handle the ice with gloves so melting is minimal.) This idea could be turned into many projects.

5. Redesign the experiment to use different sized collectors, or different lenses to concentrate the solar energy. How much energy is lost if lenses are used?
6. Try filtering the light before it reaches your collector. Sheets of colored cellophane could be used. What colors allow the greatest energy transmission? absorption? Does the filter material itself (i.e. cellophane, plastic, glass, etc.) make a difference?
7. Assuming that your collector design is a very accurate device, use the accepted value of the solar constant and the atmospheric absorption to calculate the energy absorbed by different transparent materials like plastic, Plexiglass, crystals, gelatin, etc. Note: even if your collector does not give the accepted solar constant value, as long as it is constant, this activity can still be done. Just use your "corrected" solar constant value instead of the accepted value.

Data Sheet and Calculations

Calculations: Follow the calculations on the data sheet. These will give you a step-by-step method for determining the solar constant from the data you've gathered from your simple collector.

Volume of water used:____________________liters

Mass of water used:______________________kilograms

Exposed surface area:_____________________m^2

Trial #	Initial Temp. °C	Final Temp. °C	ΔT°C	Elapsed Time (s)
1				
2				
3				

Average ΔT/sec

I. Trial #1: $\frac{\Delta T_1}{elapsed\ time} =$

Trial #2: $\frac{\Delta T_2}{elapsed\ time} =$

Trial #3: $\frac{\Delta T_3}{elapsed\ time} =$

II. Average of the 3 ΔT/time calculations=______°C/s

The specific heat of water is 4186 J/(kg°C). Therefore the energy absorbed by your water per second is:

$$4186 \times \frac{J}{kg \times {}^{o}C} \times your\ mass(kg) \times \frac{average\ \Delta\ T}{time}$$

$$\frac{Energy}{s} = \underline{\qquad\qquad\qquad} \frac{J}{s}$$

Average energy collected per unit of surface area is:

$$\frac{Energy}{s} \div your\ collection\ area\ (m) = \underline{\qquad\qquad\qquad} \frac{J}{s \cdot m^2}$$

This is your uncorrected solar irradiation for the earth's surface. Both the earth's atmosphere and the glass bottle have absorbed some of the incoming solar radiation and therefore won't show up as energy absorbed by the water. If other materials are used for your collector, then these next calculations may not be valid and more research will probably be necessary.

Multiply your uncorrected solar irradiation by 2 to correct for the glass and also by 1.4 to correct for the atmosphere:

$$solar\ \ constant\ =\ irradiation \times 2 \times 1.4$$

$$\underline{\hspace{3cm}} = \frac{J}{s \cdot m^2}$$

The accepted value of the solar constant is about 1376 W/m^{2}.

Then your % difference is:

$$\frac{your\ \ solar\ \ constant - 1376}{1376} \times 100\ =\ \underline{\hspace{3cm}}\%$$ *(include your sign)*

Questions and Interpretations:

1. Detail as many reasons as possible why your value of the solar constant differs from the accepted value.
2. Use the formulas for surface areas of spheres, earth-sun distance, geometry, etc. to find how much energy is being released per second from the surface of the sun.
3. Use the formula for the surface area of a sphere to approximate how much solar energy is received by the earth each day. (Remember that only a half of the earth is exposed to the sun at any given time.)

Activity 4

Luminosity of the Sun and Stars

Relevant Reading

Chapter 1, section 4; Chapter 2, sections 2, 3, and 4; Chapter 3, sections 1–4

Purpose

Two different types of photometers will be described here with slightly different purposes in mind. One is for bright objects such as the sun, moon, close lights, etc., and the other is for very dim light comparisons such as stars in the night sky. The second type is easier to make and use, so it will be described first.

Materials

Dim Light Comparator

- 2 index cards per student
- scissors or paper punch
- cellophane
- glue

Bright Light Photometer

- aluminum foil
- block of paraffin
- rubber bands
- nail or knife
- different wattage light bulbs

Procedures

A. Making a dim light comparator:

1. Get 2 3”x5” index cards and with them aligned, cut 5 holes about 10 mm square (or round) equally spaced across the card.
2. Separate the cards and across all 5 holes on one card, place a strip of clear cellophane so that all 5 holes are covered. Glue it in place.
3. With a shorter strip of cellophane, cover 4 of the holes, leaving the first hole with only one layer of cellophane, but the next 4 holes having 2 layers. Glue this strip into place.
4. Repeat this process so that each hole has one more layer of cellophane than each preceding hole—1 layer for hole 1, 3 layers for hole 3, etc.

5. Place the second card over the first so that the cellophane is sandwiched between them and tape the edges closed.
6. When using this with dim objects, look at the objects through the different holes until it is just barely visible. After this is calibrated as described below, this can be used to measure the visual light magnitude of different stars.

Calibration:

1. Take your comparator out on a clear night, preferably to a location with little light pollution and locate the constellation of Draco (the Dragon) or the asterism called the Big Dipper.
2. If Draco is used, find the 4 brightest stars in the head. The brightest star should be visible through the fifth hole, but if not, move to the fourth hole, and so on until it is visible. Mark the hole with a "2.2" value.
3. Use this table to calibrate the other holes.

Stars in Draco	Visual Magnitude	Approximate Magnitude
Elatin	2.2	2
Rastaban	2.8	3
Grumium	3.8	4
Kuma	4.9	5

4. If the Big Dipper is easier to find, calibrate the holes in the same way using these values:

Stars in the Big Dipper	Visual Magnitude	Approximate Magnitude
Dubhe	1.8	2
Alkaid	1.9	2
Mergret	3.3	3
Alcor	4.0	4

5. If you feel you need a more accurate calibration, or you modify the comparator to have a wider range, here are some more values.

Star	Constellation	Visual Magnitude
Sirius	Canis Major	–1.46
Arctaurus	Bootes	–0.04
Vega	Lyra	+0.03
Betelgeuse	Orion	0.5
Antares	Scorpius	0.96
Spica	Virgo	0.98

Polaris	Ursa Minor	2.02
Sadalmalik	Aquarius	2.96
Alberio	Cygnus	3.08
Alcor	Ursa Major	4.01
Kuma	Draco	4.88

6. The list below gives some magnitudes for a number of the more familiar objects.

Apparent Magnitude	Object
–26.7	Sun
–12.5	full moon
–1.5	Sirius (brightest star)
+0.5	Betelgeuse
2.0	Polaris (the north star)
6.5	limit of unaided eye under ideal conditions
9.0	limit of 7x50 binoculars
13.0	visual limit of 8” telescope
24.0	photographic limit of 200” telescope
28.0	limit of the Hubble Space Telescope

Using the comparator:

1. Once calibrated, the comparator can be used to find the magnitudes of any of the stars you see. The accuracy will depend on several factors:

   The “seeing” conditions of the sky being the same as the night the device was calibrated (or recalibrate with each use)

   How well the calibration was done

   Your judgment in matching the visibility through the holes

2. Measure a number of well known stars and compare your values to the accepted values from a reference book or chart. You should be able to get the whole number values fairly well after a little practice, but fractions will be difficult without more sophisticated techniques.

3. Use the comparator to find the magnitude of lights in your neighborhood. Look at bulbs of the same wattage but placed at different distances from you. By carefully measuring the distances and the magnitude, you might be able to determine the mathematical relationship that describes brightness and distance.

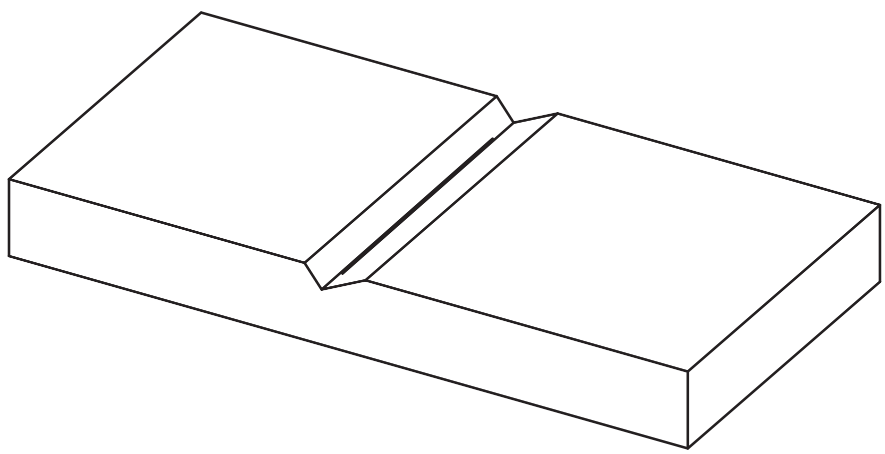
4. Use your device to place lights of different wattages (maybe 60 watts and 100 watts) at different distances so that they appear equally bright. Try

this with several wattages and again see if you find the brightness-distance relationship.

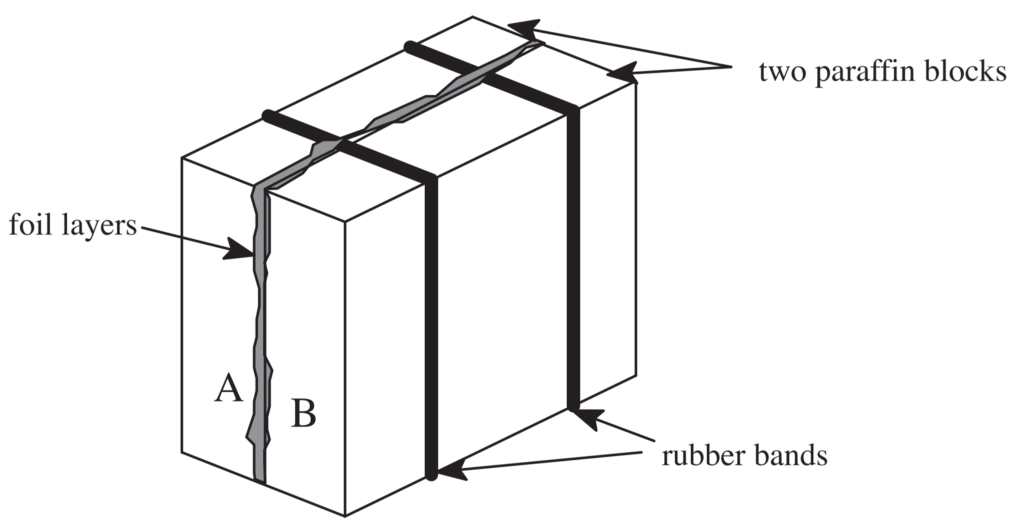
5. Does the size of the light source make a difference and how could this be tested? Explain how a large object and a small one could appear equally bright at the same distance. What could this reveal about the actual energy released by each object?
6. How could you modify the design of this comparator to measure much brighter objects?

B. Making a bright light photometer:

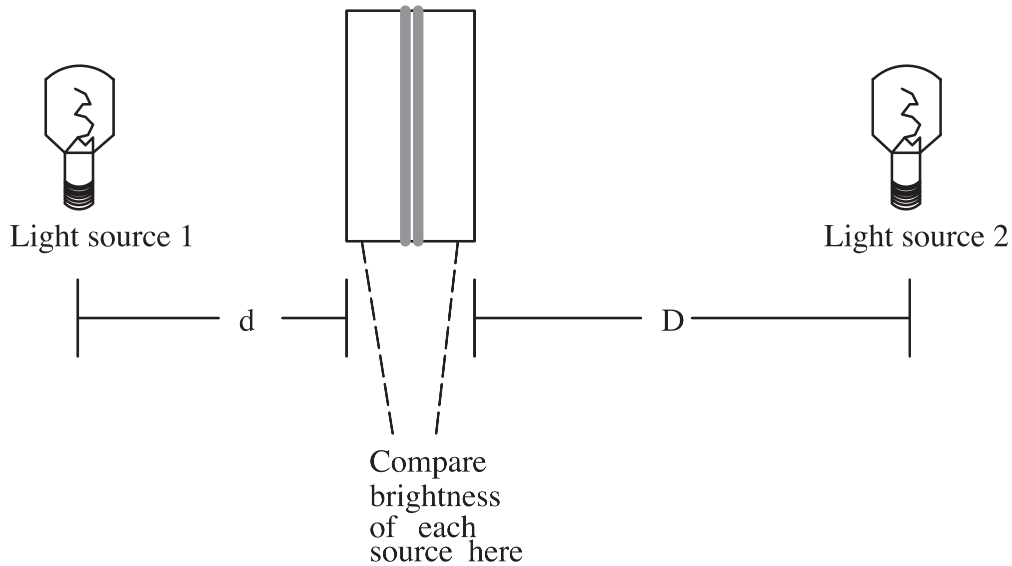
1. Obtain a piece of aluminum foil about 60 mm × 120 mm, two rubber bands, and a block of paraffin wax also 60 mm × 120 mm.
2. Make a deep scratch in the center of the wax block with a nail or point of a knife. Snap the block in half along the sharp edge of a table or desk.



3. Fold the foil in half to form a 60 mm × 60 mm square, shiny side out, and place it between the paraffin blocks.
4. Rubber band the unit together near the edges



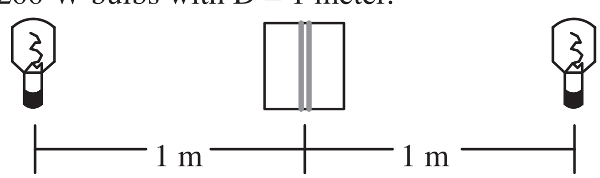
5. Lights placed on opposite sides of the foil illuminate the blocks and the brightness of the wax at points A and B can be compared. See the arrangement below.



6. 2 equal wattage bulbs placed at the same distance should produce the same brightness in the photometer.

Using the Photometer:

1. Obtain four or five light bulbs of various wattages such as 25 W, 50 W, 75 W, 100 W, and 200 W.
2. To test the photometer, place it midway between two equal-wattage bulbs. Use 100 W or 200 W bulbs with D = 1 meter.



The brightness of each side of the photometer should appear the same. If not, check the wattages of the bulbs, check the distance, and check the thickness of each side of the photometer. All three of these parameters should be the same.

3. With a working photometer, place the lowest wattage (25) bulb at 0.5 m from one side of the photometer. On the other side, place a higher wattage bulb and adjust its distance until the photometer shows equal brightness on both sides. Record the distance in the table below.
4. Repeat the process in step #3 with as many bulbs as possible, recording the distances you find in the same table.

Watts	Distance	Watts	*Multiple of low-watt bulb	Distance	*Multiple of 0.5 meters
EXAMPLE: 25	0.5 m	100	4	1 m	2
25	0.5 m				
25	0.5 m				
25	0.5 m				
25	0.5 m				
25	0.5 m				

5. Look carefully at the values in the starred columns. What appears to be the mathematical relationship between the starred columns? (It should be very close to a squared relationship.)
6. Now that the brightness-distance relationship has been established, the photometer can be used to determine the brightness of the Sun. Take the photometer and a 200 W bulb outside on a sunny day.
7. Face one side of the photometer at the Sun, and place the lighted bulb on the other. Have an assistant move the bulb towards or away from the photometer until the brightness from the Sun and the bulb match as closely as possible. Measure the distance from the bulb to the photometer.
8. Repeat the process in step #8 several more times and record the average distance of the bulb in centimeters.
9. The Sun is about 1.5×10^{11} m from Earth (150,000,000,000 m !). Use your average distance in m from step #8 and determine the multiple needed to equal the solar distance. For example, if the bulb distance is 3 meters, then $1.5 \times 10^{11} / 3 = 5 \times 10^{10}$. This value, 5×10^{10}, is the number of "bulb distances" to the Sun.
10. Now use the mathematical relationship that was determined in step #5 to find how many 200 W bulbs would be needed to equal the solar luminosity.
11. Since a 200 W bulb was used to compare brightness with the Sun, the value calculated in step #10 is based on units of 200 W. Simply multiply the value from step #10 by 200 to convert to 1-watt units.
12. State the final solar luminosity in 1-watt units.

Solar Luminosity = ____________________________ watts

Activity 5

Seeing at Different Wavelengths

Purpose

One of the keys to learning about the Sun is to view it in different wavelengths of light. The views can be quite different, and so are views of objects on Earth in different wavelengths. This activity examines objects through a filter set of colored and specialized filters and illustrates how science users different wavelengths to selectively study features of the Sun.

Materials

A. Colored Acetate Filters

2 to 4” × 5” cards with pre-punched holes (about 15 mm in diameter)

(An alternative to the above card set up is to mount each of the filters separately in a 35-mm slide mount. This has the advantage of being able to use some of these with a slide projector, but the disadvantage of more individual items to use.)

tape

30-mm squares of colored acetate: 1 each of red, green, blue. Use of better quality really helps here, especially with blue. Colored cellophane is OK, but only if acetates can’t be found.

B. Diffraction, Polarizing and Solar mylar Screen Filters

all of the above

30-mm square of holographic diffraction grating

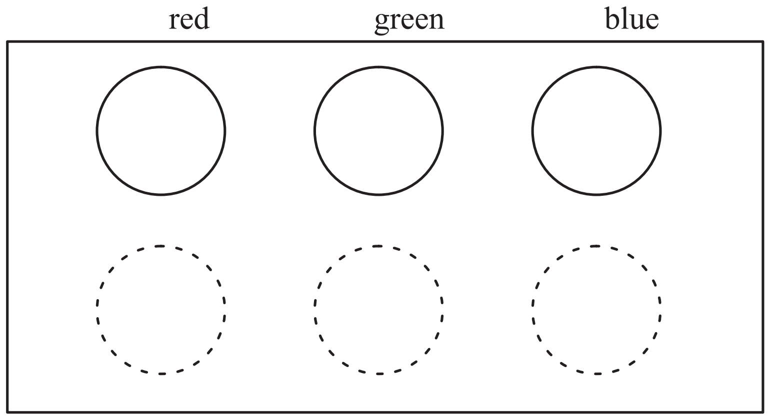
30-mm square of polarizing material

30-mm square of SolarSkreen™ or solar mylar

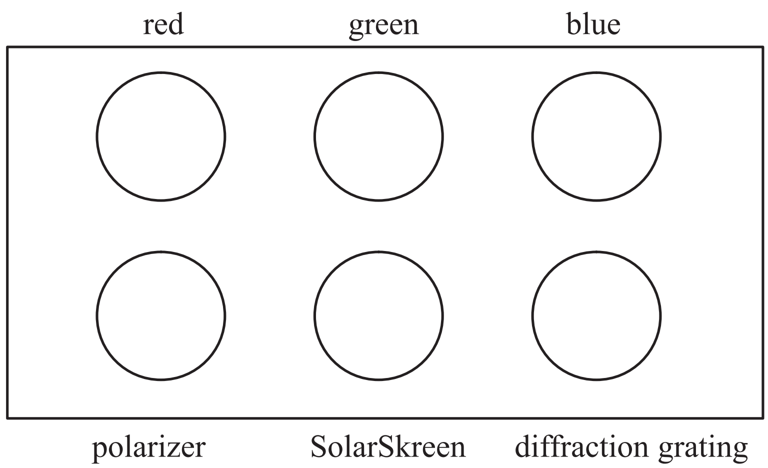
Procedures

Making the filter set:

1. If only 3 holes are necessary for the 3 colored acetate sheets, arrange them as shown:
   Try to put the red and blue at positions that fit both eyes of the user at the same time. The filter card can then be used as 3-D glasses with many of the 2-color 3-D images that are available.



2. Tape an edge or corner into place for each color, being careful not to cover the hole.
3. If any of the other filters are to be used, place them onto the card now.



4. Place the second index card over the first with the filters sandwiched inside and tape the edges of the card closed.

Using the Colored filter set: (*Don't look directly at the sun with any of the filters except the SolarSkreen filter Other filters can be used with the SolarSkreen but not without it.)

1. Examining colored objects around you and compare how different things look if only one color is transmitted to the eye. Can you generalize about what you see?
2. Examine colored photos and plates in your text books, or colored photos and slides prepared by your teacher. Note carefully the position of the red color in the original, white light pictures, and then describe what happens when the red filter is used. What happens to the red colors when the green filter is used? the blue?
3. Examine the colors in the photo that are not part of the filter set, such as yellow or purple. How do these show up with each of your filters?

4. Write out a general descriptive explanation of what happens when various colored filters are used.
5. If your teacher can provide a projected spectral image from a piece of holographic diffraction grating, look at it with each of your colored filters and describe how they effect your view of the spectrum.
6. Use your colored filters in conjunction with a spectroscope (see Activity 1)
7. Brainstorm other possible uses.

Using the Polarizer Filter Set:

1. Find a spot of bright glare or reflection from a shiny surface. Automobile chrome and swimming pools are great. Rotate the polarizer as you look through it at the glare. What happens to the glare or reflections as the rotation is made?
2. Examine transparent objects such as auto window glass, plastic boxes, or cellophane by using the same rotation technique. Are there any characteristics of these material that weren't visible before?
3. Use a second piece of polarizer to examine transparent objects placed between the filters. Rotate the filters to see some spectacular effects.

Using the SolarSkreen™ filter set:

SolarSkreen is used to view the Sun directly. Larger pieces can be placed over the objective end (the end away from your eye) of a small telescope or binoculars. Be sure you know how to use this filter with these devices as permanent eye damage could result from improper use. With binoculars, be sure to cover both objective lenses, either both with SolarSkreen, or one with SolarSkreen and the other with a tight fitting lens cap.

1. Use the SolarSkreen to look for large sunspots or groups. Small spots will not be visible without some type of magnification, and if the Sun is at or near a sunspot minimum, this could be a disappointing activity.
2. If spots are visible, does the addition of any of the colored filters make it easier or harder to see them?
3. Add the diffraction grating or polarizer to the SolarSkreen. Explain what happens.

Activity 6

The Earth-Sun Orientation

Resources

Chapter 4

Purpose

A plot of the Sun's path across the sky illustrates many of the complex apparent motions of the Sun and Earth, which leads to understanding of seasons.

Materials

a clear plastic hemisphere from 150 mm to 450 mm in diameter. Clear salad bowls, plastic covers for bird feeders, etc. can be found at hardware stores.

a water soluble marker or grease pencil

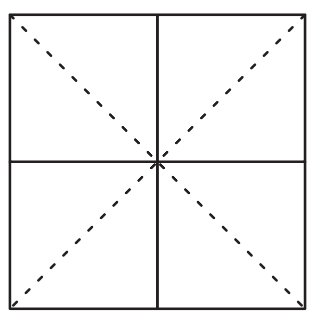
a square sheet of cardboard large enough to act a a base for the dome.

tape

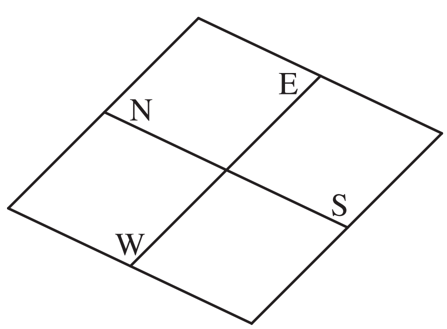
a magnetic directional compass

Procedure

1. Mark the center of the cardboard by finding the intersection of the lines from diagonal corners or midpoint lines from the sides and draw the lines connecting the midpoints of opposite sides.



2. Mark one line with North-South and the other East-West as shown:



3. Tape the dome in place over the center of the cardboard so it won't move.
4. Use the compass to mark a N–S line on the ground outside. A chalk line on the side walk, a driveway, or parking lot in the open sun will last for several days of observations. However, the compass needle may be attracted to iron material used to reinforce the concrete, etc. A technique known as the "Minimum shadow method" is easiest to use when a compass can't be used, but takes several hours to establish an orientation line.
5. Set the cardboard unit on the line so that the edge pointing N–S is on the N–S line on the ground.
6. Plot the position of the sun as described in the following steps.
7. Hold the tip of your marker close to the dome but don't touch it.
8. Carefully move the marker until the shadow of the tip falls right on the center mark of the cardboard.
9. Touch the marker to the dome when the shadow of the dot would fall right on the center mark. If it is not right, make a new dot and erase the old.
10. Repeat the steps 8, 9, 10 every 10 min for as long as possible (at least 30 min = 4 dots). It would be really good if this could be done every half-hour from sunrise to sunset.
11. After collecting as many dots as possible on one day, remove the dome from the cardboard and connect the dots on the inside of the dome. Label the line with the date and the time.

Long term extensions:

1. Wait one week or one month and repeat the data collection. Do this for several weeks or months. How do you account for the differences in the plots?
2. Make a plot of only one time each day, say 12 noon. Do this for as many days as possible—a plot for an entire year would be quite a feat! Try to predict what the plot will be if an entire year of data points could be collected.

Questions

1. Predict where the plotted points would be during different seasons and explain why.
2. Predict where the plotted points would be if you lived at

   a) the North Pole

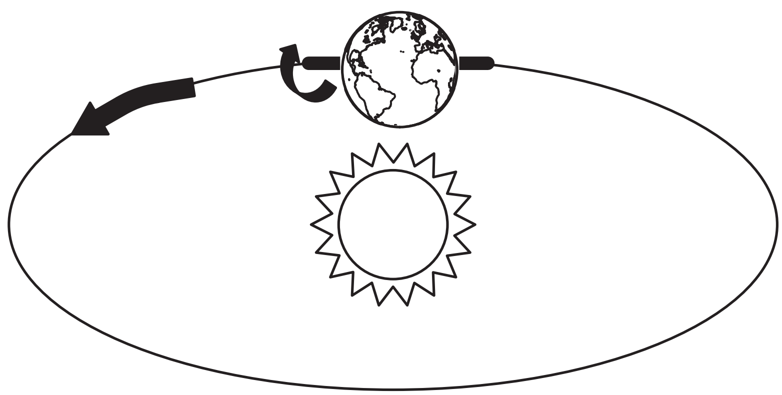
   b) on the equator

   c) in the southern hemisphere.
3. How would the predicted points in #2 change for different seasons?
4. Predict where the plotted points would hit your "horizon" at the edges of the dome for various days of the year such as the first day of winter,

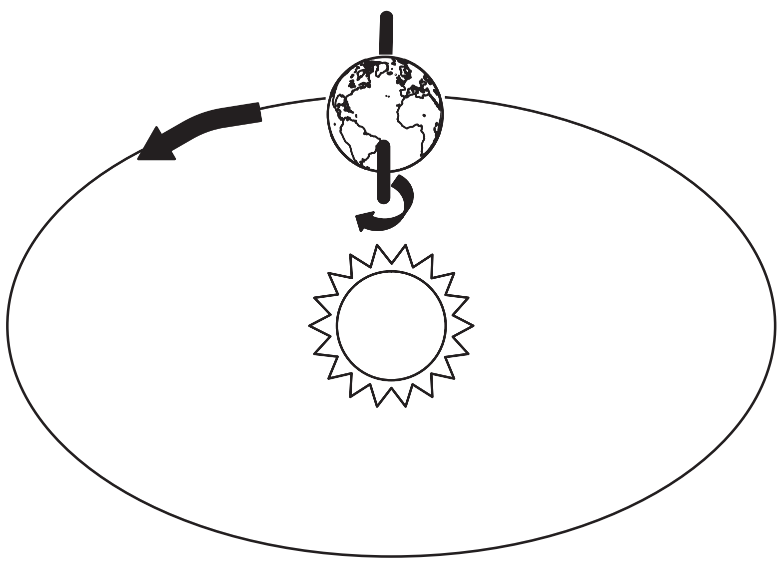
spring, summer and fall, or better yet, at the days of equinox and the solstice.

5. Use your plots and predictions to explain the importance of how Earth and Sun are lined up in space.
6. What would the seasons be like if Earth had no tilt to its axis of rotation?
7. What would the seasons be like if Earth's axis were

 a) parallel to the orbital path



 b) always pointed at the sun?



Activity 7

The Effect of the Solar Wind on the Geomagnetic Field

Purpose

To monitor changes in the earth's magnetic field and relate these changes to solar events such as flares. Many variations of this design are in use by amateurs because of its simplicity, but now with the availability of inexpensive and sensitive Hall-effect sensors that easily interface to home computers, it should be possible to make more quantitative measurements of changes in the geomagnetic field due to solar wind. By monitoring changes in the geomagnetic field, aurorae and related effects can be forecast and studied.

*This activity is based on the jam-jar magnetometer described by Ron Livesey in the article "A Jam-Jar Magnetometer as 'Aurora Detector' " in the October 1989 issue of *Sky and Telescope*. Another magnetometer is described in the October 1993 issue of *Sky & Telescope*. This device is a bit harder to construct and although it requires some knowledge of electronics, it is suitable for high-school students.

Materials

1 glass jar 80–100 mm in diameter, 200 mm high with a non-magnetic lid

300 mm of thin nylon thread

200 mm of copper wire

1 small glass mirror approximately 5 mm wide by 10 mm tall painted flat black with a 1 mm wide clear slit in the center (a first surface mirror is best but standard mirror glass will be OK)

1 small bar magnet 20-mm to 30-mm long

cardboard and glue

ruler or meter stick

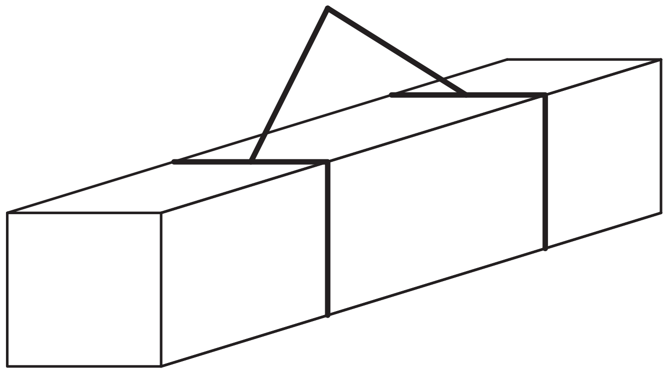
light source such as a flashlight, or a laser

A 1-m by 0.5-m vibration-free location, away from electrical and magnetic interference

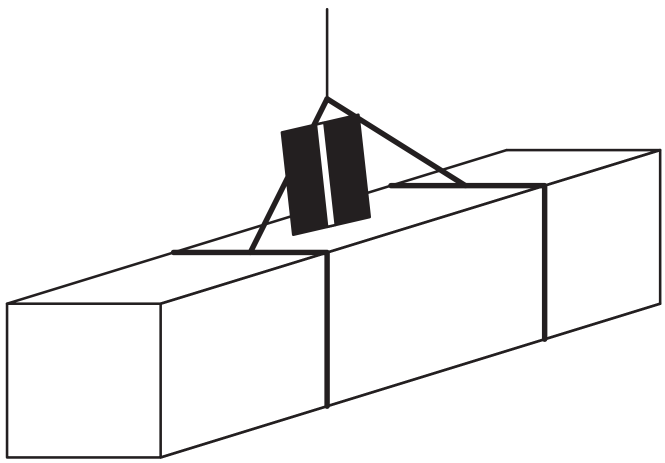
Procedures

Assembly

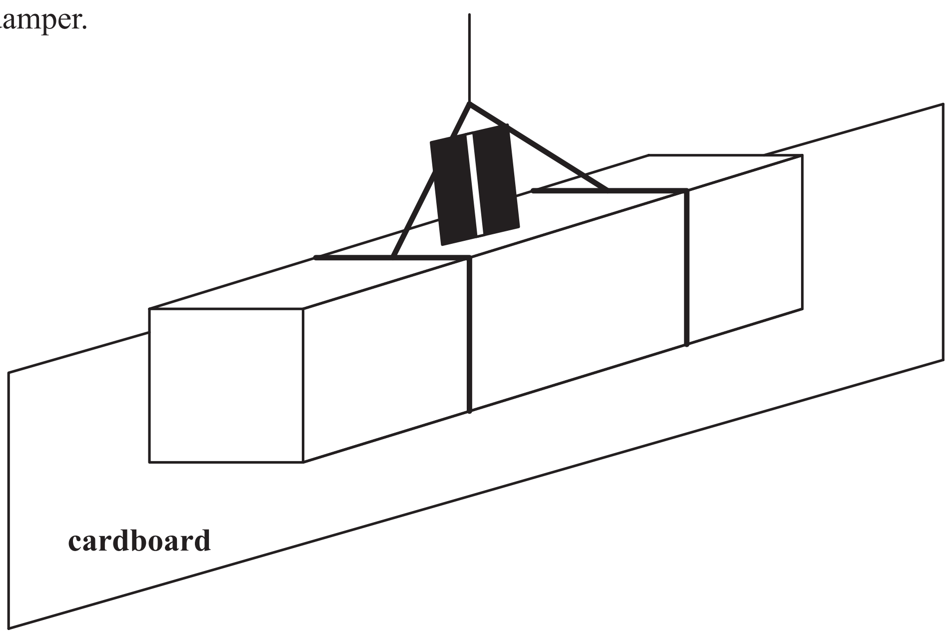
1. Use the copper wire to form a cradle for the magnet as shown:



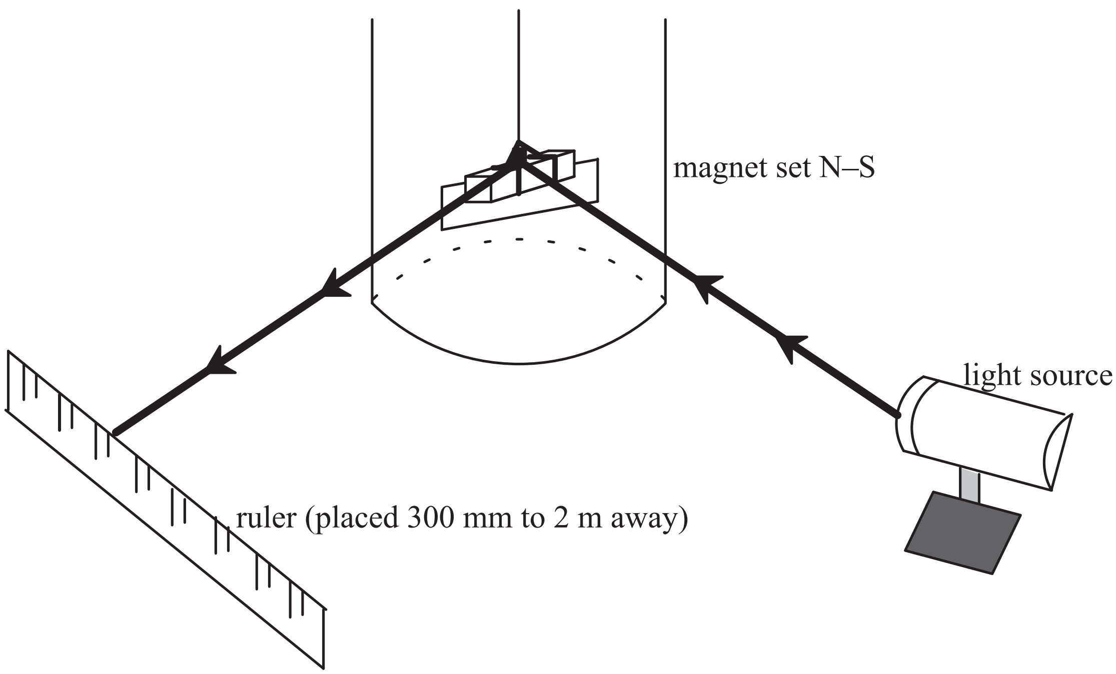
2. Tie one end of the nylon thread to the cradle and glue the mirror onto the top of the magnet against the cradle wire. Make sure the unpainted slit is vertical.



3. Glue a rectangle of cardboard to the back of the magnet to act as an air damper.



4. Drill or punch a small hole into the center or the jar lid and pass the free end of the nylon thread through it from inside.
5. When the magnet unit swings freely inside the jar with the lid in place, glue the thread to a toothpick or match on the lid.
6. Use a laser light or prepare a light source by cutting a mask with a narrow slit using razor blades or small squares of aluminum cut from a soda can to make a narrow beam.
7. Set up the apparatus as shown. It could be mounted on a board or table for less set up time when used.



Using the magnetometer: Since many factors can affect the orientation of the magnet, including cars, tools, appliances, vibrations, etc., realize that this device is made to detect changes in the direction of the geomagnetic field and not give a quantitative measure of strength.

1. Set the light to produce a bright spot on the ruler (not close to an end). Record the reading, date, and time.
2. Record data again later, making sure that no part of the apparatus has been moved. Record data hourly, unless you suspect that a magnetic disturbance is occurring, then more frequent readings should be taken.
3. In order to make the scale readings more useful and easier to compare with others' observations, it's best to convert the bar magnet's deflection change to an angular value. Using L as the distance from the mirror slit to the scale and S as the scale reading, then

$$D = 1719 \times \frac{S}{L}$$

*(D is given with formula in minutes of arc.)

4. Convert the time to UT, Universal time, and make a plot of D vs. UT.
5. Relate the data you've collected to the published information on solar flare activity and/or the reported auroral sightings.
6. To get an idea of the relative sensitivity of your instrument, move around an iron bearing object or another magnet at different distances from the magnetometer and careful note any deflection. Is it possible to show the inverse-square law for magnetic field strength with this device?

*Some simple geometry and the law of reflection will show that a deflection of D in the magnet will produce a 2D deflection at the scale.

Then, in radians,

$$2D = \frac{S}{L}$$

or $$D = \frac{S}{2 \times L}$$

Converting to arc min:

$$D = \frac{S}{2 \times L} radians$$

Therefore

$$D = 1719 \times \frac{S}{L}$$

Activity 8

Determining the Rotation Period of the Sun

Relevant Reading

Chapter 2, section 3

Purpose

Determine the rotation period of the Sun. Although numerous methods for accurate measurement are used in solar research, the method described here, using photographs taken over several days, will allow determination to within an Earth-day.

Materials

Photo set that shows at least one solar feature that can be followed over a several-day period. For real challenge, take the photos yourself, or make a simple projection sketch of sunspots over several days.

1 sheet of clear plastic used for overhead transparencies or viewgraphs, or something similar such as a clear plastic report folder

a mm ruler, compass and protractor

a fine-tipped marking pen suitable for plastic

graph paper with 1-mm squares

Procedures

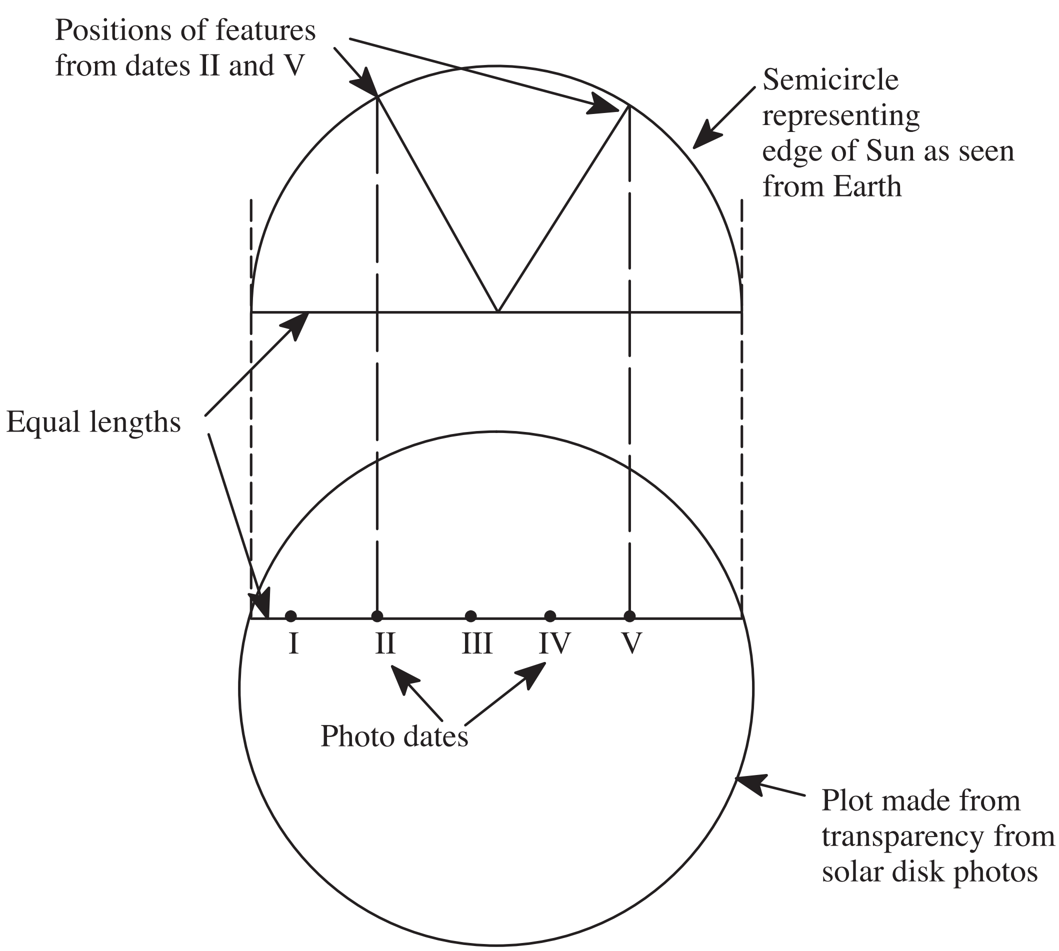
1. Measure, to the nearest millimeter, the diameter of the Sun on the photo taken near the middle of the data period.
2. Use a compass and draw a circle with the same diameter on the transparent sheet.
3. With the circle aligned over the photo on the date used for the diameter, trace the axis orientation marks onto the transparency.
4. Pick a solar feature that traverses the solar disk for as many days as possible. Align the circle on the transparency over each successive photo and carefully mark the position of the chosen solar feature along with its date.
5. Carefully draw the best fitting straight line through the marked positions and measure its length across the circle as accurately as possible. (Note that (a) unless the chosen feature follows right along the solar equator, the length of this position line will be less than the measured solar diameter, and (b) the line should be perpendicular to the solar axis.

6. Because the sun is a sphere, features near its edge (limb) will be foreshortened and motion there will not appear the same as motion near the center of the disk. To compensate for this, the positions on the transparency will be translated to a semicircle that represents the path of the solar feature viewed edge-on from Earth.

7. Using the measure of the line representing the solar feature's path as a diameter, draw a semicircle on a piece of graph paper. This semicircle represents the edge of the Earth-facing surface of the Sun along the feature's path.

8. Carefully transfer the positions marked on the transparency to the diameter line of the semicircle and again indicate the dates.

9. Chose two widely separated positions, avoiding those that are close to the limb (position accuracy will be less here) and mark their positions on the semicircle by drawing a perpendicular to the diameter through the position point to the semicircle. These markings indicate the actual position of the solar features on the Sun's surface.



10. Now connect these to points to the center of the diameter line so that a central angle is formed. Measure this angle with a protractor as accurately as possible (0.1 degrees can be estimated).
11. Calculate the number of degrees traveled per day for this solar feature.
12. If more than one feature is distinguishable in the photos, or another set of photos is available, repeat the process and then average the calculations of the degrees travelled per day.
13. One full solar rotation is 360° so instead of degrees per day, the number of days for a full rotation should also be calculated. Do this by dividing 360 by the value found for the degrees travelled per day.

Discussion

Because all the photos or observations of the Sun are made while our Earth is moving through space, the calculations performed here actually have this planetary motion "hidden" in them. The Sun rotates on its axis in almost the same direction as the Earth revolves around the Sun in space. Therefore, any features noted on the solar surface will have to travel more than 360° to get back to a place that appears the same as viewed from Earth. The name given to the time periods that include the Earth's motion is called **synodic**, while periods found related to the "fixed" background of stars is called **sidereal**. Because the Sun has had to rotate more than 360° to "catch up" with the moving Earth, the synodic period is longer than the sidereal period by about 2 days.

To calculate the sidereal period from the synodic value,

Let R = sidereal period
S=synodic period
Then $R = S \times 365.26\ (S + 365.26)$
The value of 365.26 is the number of days in an Earth Sidereal year.

Solar astronomers have found that the Sun exhibits a differential rotation. That is, it rotates at different rates at different latitudes, with the faster rates nearer the equator. An extension to this activity would be to analyze features from several latitudes and then determine the solar rotation rate as a function of latitude.

Activity 9

Radiation Hazards in Space

Relevant Reading

Chapter 4, section 2

Purpose

To become familiar with the relative hazards associated with space travel, and the attendant personal and governmental problems that impact that travel.

Materials

Cardboard to mount game board sheets

Markers or crayons to color game board

Small colored paper squares or paper clips, distinctive for each player

Tally Cards, cut to size, and pencils

Chance cards, cut to size

one die

Procedures

1. Groups of two to four can play this game. Duplicate materials as needed for other groups.

   Mount the game board on a piece of cardboard. Color the board. (Mars is the "red planet." What color would Earth be? the Sun be?)

   Cut out Tally Cards and *Chance* cards. Each player needs a Tally Card and a pencil. Cut out *Chance* cards and place face down in a pile. You may want to double the number of *Chance* cards by copying before cutting. There are several blank cards that can be used to make your own *Chance* cards.
2. Have group read over directions for the game. A game will take 10–15 minutes to play.
3. Review the scoring and plotting when a game is over.
4. Have Fun!

Rules of the Game

Object

The idea is to get from Earth to Mars and back along one of two pathways. Along the way you will acquire Radiation Points (RPs) and these are detrimental to your health. You will also acquire Mission Points (MPs) for significant events that measure your success.

When you have finished the game, plot your total Radiation Points and Mission Points on the back of the Tally Card to see how you did and who "won."

Procedure

From two to four players may play at one time.

Use any small object for each person's marker that moves on the board.

Use one die and begin play. Move the marker the number of spaces on the board.

Each player must select which path he/she will take to Mars at his/her first turn. If a player is sent back to Earth, that player may choose either path to proceed.

You *must* stop on each shaded space, regardless of your roll, and record your points. In your next turn, roll the die and proceed as usual.

If a player lands on *Chance*, draw a card off the top of the Chance pile, do as it says, and return the card to the bottom of the pack.

When one player finishes the game (you do not need an exact roll to move to the last space), all other players continue to play in turn until each has finished and received all points.

Scoring

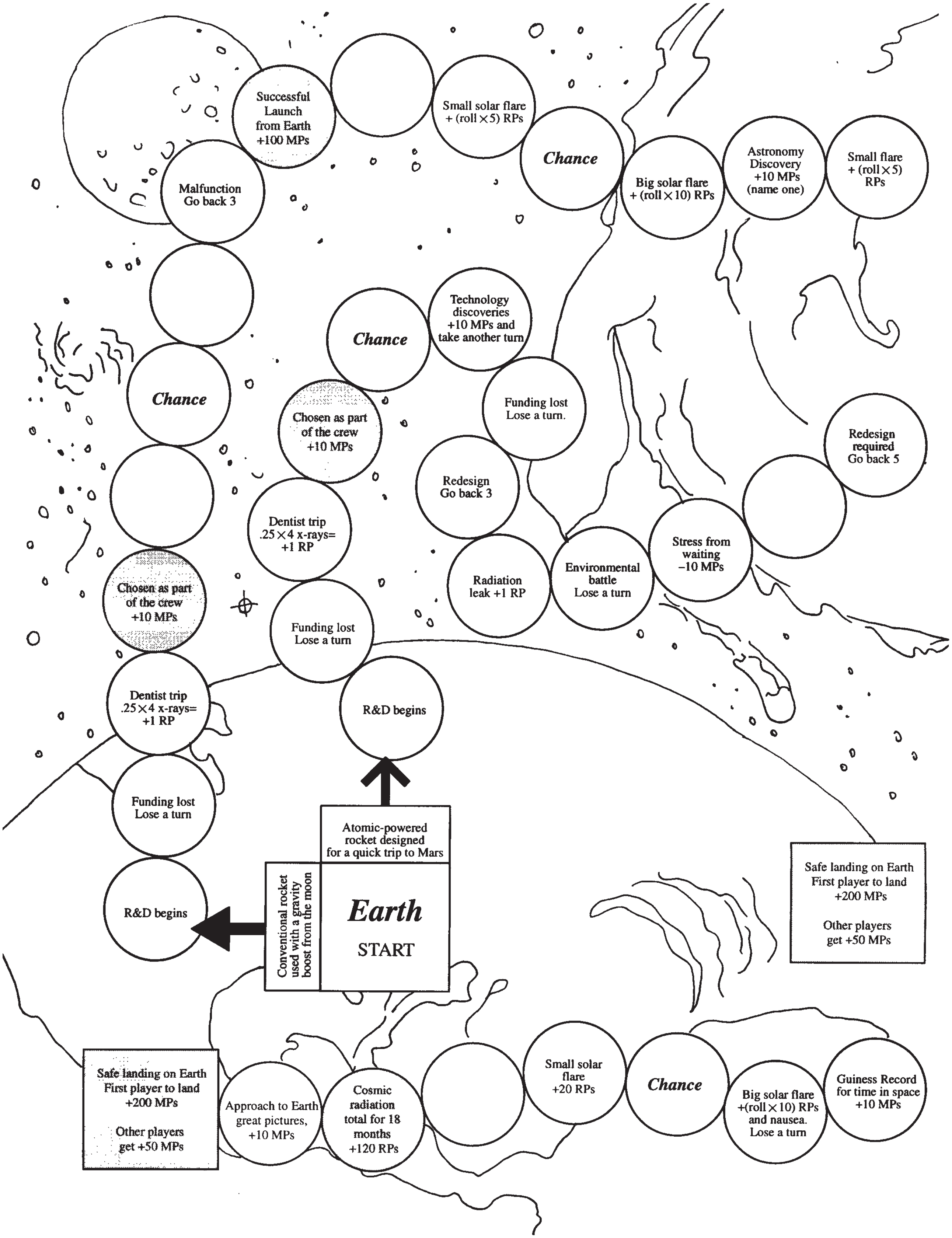
Each player must record all Radiation Points and Mission Points on his/her card. At the end of the game, each totals his/her own points and plots the two values in a single point on the graph on the back of the Card. The player with the point that is most in the upper left-hand corner of the graph is the winner.

Record Mission Points for launching, landing, etc. next to the appropriate space on your tally card.

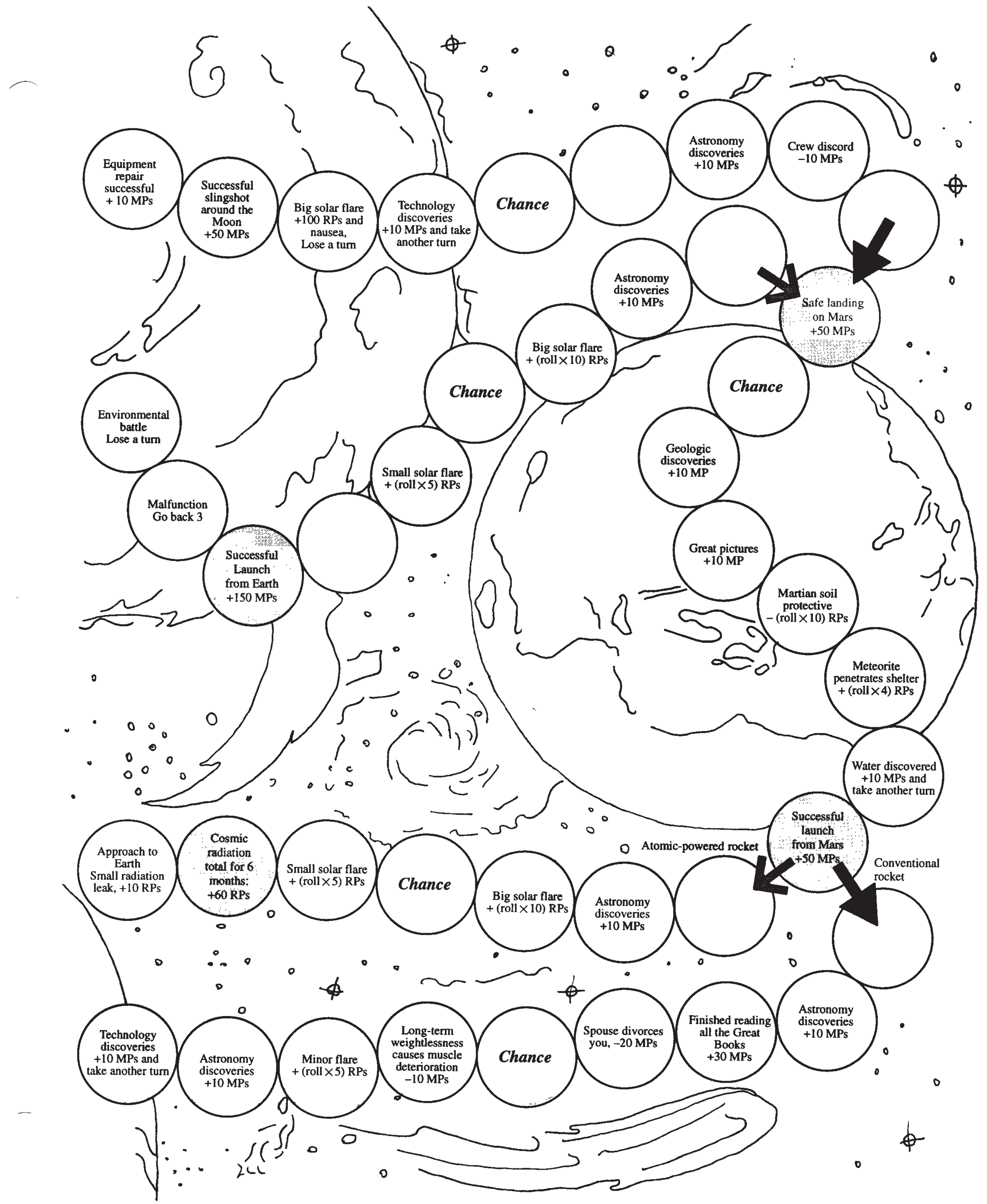
If you are sent back to Earth with a *Chance* card, your score card continues to accrue Mission Points and Radiation Points. You do *not* clear your card to 0's.

Here are some real numbers for radiation exposure (from NASA)

TYPES OF EXPOSURES	REM
Transcontinental Round Trip by Jet	0.004
Chest X–Ray (Lung Dose)	0.010
Living One Year in Houston, TX	0.100
Living One Year in Denver, CO	0.200
Living One Year in Kerala, India	1.300
Highest Skin Dose, Apollo 14 (Mission to the Moon; 9 day mission)	1.140
Highest Skin Dose, Skylab 4 (Orbiting Earth at 272 miles, 87 day mission)	17.800
Highest Skin Dose, Shuttle Mission 41–C (Orbiting Earth at 286 miles, 8 day mission)	0.559
Maximum Allowable in 1 Year to a Terrestrial Worker	5.000
Background radiation in 1 Year on surface of Earth	0.100



Successful Launch from Earth +100 MPs
Small solar flare + (roll × 5) RPs
Chance
Big solar flare + (roll × 10) RPs
Astronomy Discovery +10 MPs (name one)
Small flare + (roll × 5) RPs
Malfunction Go back 3
Chance
Technology discoveries +10 MPs and take another turn
Chance
Chosen as part of the crew +10 MPs
Funding lost Lose a turn.
Redesign required Go back 5
Redesign Go back 3
Dentist trip .25 × 4 x-rays= +1 RP
Stress from waiting −10 MPs
Chosen as part of the crew +10 MPs
Radiation leak +1 RP
Environmental battle Lose a turn
Funding lost Lose a turn
Dentist trip .25 × 4 x-rays= +1 RP
R&D begins
Funding lost Lose a turn
Atomic-powered rocket designed for a quick trip to Mars
Safe landing on Earth First player to land +200 MPs
Other players get +50 MPs
R&D begins
Conventional rocket used with a gravity boost from the moon
Earth
START
Safe landing on Earth First player to land +200 MPs
Other players get +50 MPs
Approach to Earth great pictures, +10 MPs
Cosmic radiation total for 18 months +120 RPs
Small solar flare +20 RPs
Chance
Big solar flare +(roll × 10) RPs and nausea. Lose a turn
Guiness Record for time in space +10 MPs



Equipment repair successful + 10 MPs
Successful slingshot around the Moon +50 MPs
Big solar flare +100 RPs and nausea, Lose a turn
Technology discoveries +10 MPs and take another turn
Chance
Astronomy discoveries +10 MPs
Crew discord −10 MPs
Safe landing on Mars +50 MPs
Astronomy discoveries +10 MPs
Big solar flare + (roll × 10) RPs
Chance
Small solar flare + (roll × 5) RPs
Environmental battle Lose a turn
Malfunction Go back 3
Successful Launch from Earth +150 MPs
Chance
Geologic discoveries +10 MP
Great pictures +10 MP
Martian soil protective − (roll × 10) RPs
Meteorite penetrates shelter + (roll × 4) RPs
Water discovered +10 MPs and take another turn
Successful launch from Mars +50 MPs
Atomic-powered rocket
Conventional rocket
Approach to Earth Small radiation leak, +10 RPs
Cosmic radiation total for 6 months: +60 RPs
Small solar flare + (roll × 5) RPs
Chance
Big solar flare + (roll × 10) RPs
Astronomy discoveries +10 MPs
Technology discoveries +10 MPs and take another turn
Astronomy discoveries +10 MPs
Minor flare + (roll × 5) RPs
Long-term weightlessness causes muscle deterioration −10 MPs
Chance
Spouse divorces you, −20 MPs
Finished reading all the Great Books +30 MPs
Astronomy discoveries +10 MPs

Health and Happiness Tally Card

+ or –	Radiation Points	+ or –	Mission Points
			Crew:
			Launch ⊕:
			Land ♂:
			Launch ♂:
	Comic Rad:		Land ⊕:

Total RPs____________ Total MPs__________

Plot your totals on the other side

Health and Happiness Tally Card

+ or –	Radiation Points	+ or –	Mission Points
			Crew:
			Launch ⊕:
			Land ♂:
			Launch ♂:
	Comic Rad:		Land ⊕:

Total RPs_________ Total MPs__________

Plot your totals on the other side

Health and Happiness Tally Card

+ or –	Radiation Points	+ or –	Mission Points
			Crew:
			Launch ⊕:
			Land ♂:
			Launch ♂:
	Comic Rad:		Land ⊕:

Total RPs_________ Total MPs__________

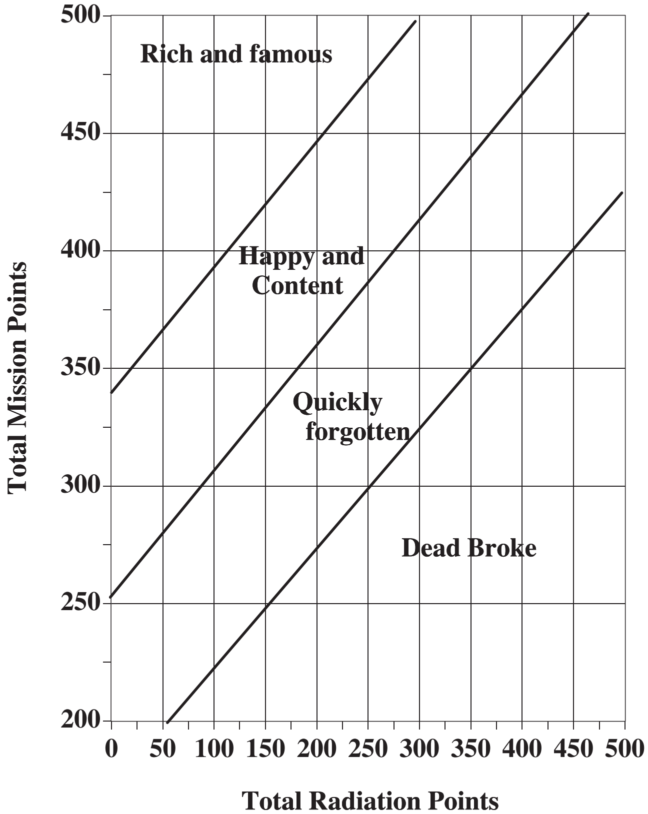
Plot your totals on the other side

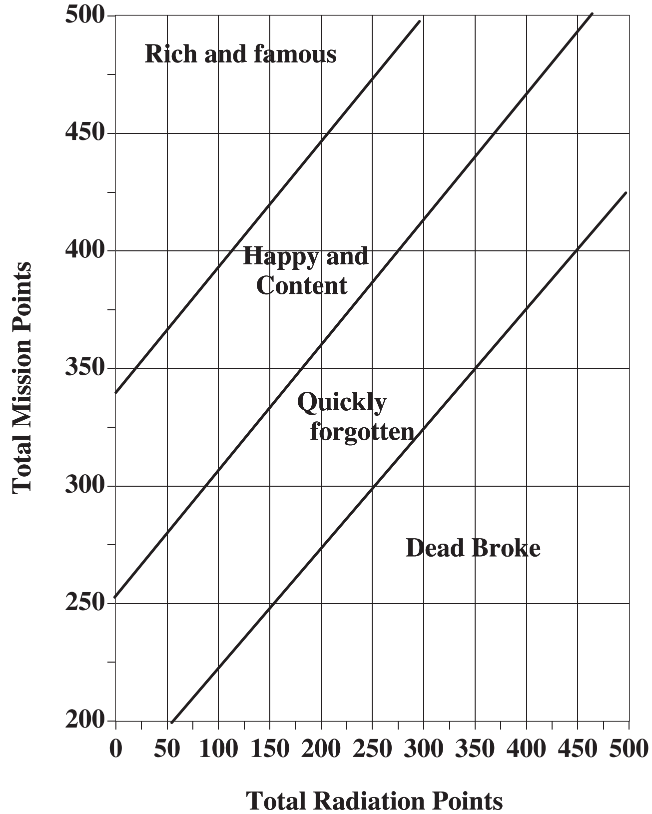
Health and Happiness Tally Card

+ or –	Radiation Points	+ or –	Mission Points
			Crew:
			Launch ⊕:
			Land ♂:
			Launch ♂:
	Comic Rad:		Land ⊕:

Total RPs_________ Total MPs__________

Plot your totals on the other side


Rich and famous
Happy and Content
Quickly forgotten
Dead Broke
Total Mission Points
500
450
400
350
300
250
200
0 50 100 150 200 250 300 350 400 450 500
Total Radiation Points


Rich and famous
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Total Mission Points
500
450
400
350
300
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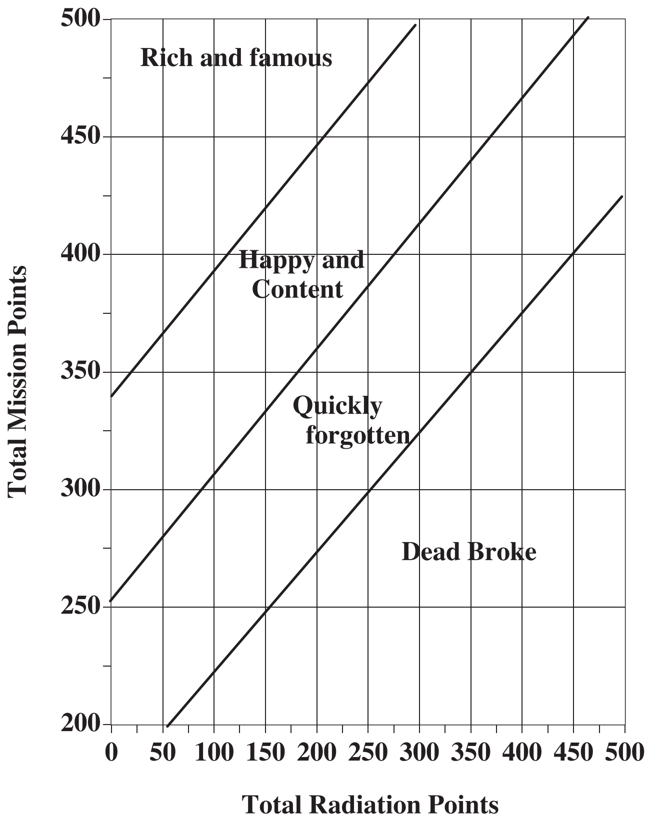
200
0 50 100 150 200 250 300 350 400 450 500
Total Radiation Points


Rich and famous
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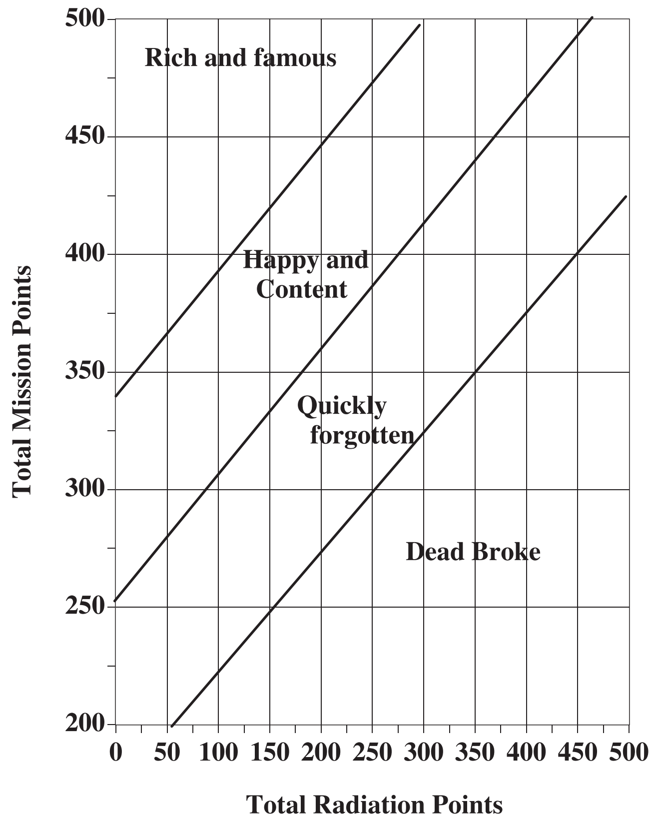
Total Mission Points
500
450
400
350
300
250
200
0 50 100 150 200 250 300 350 400 450 500
Total Radiation Points


Rich and famous
Happy and Content
Quickly forgotten
Dead Broke
Total Mission Points
500
450
400
350
300
250
200
0 50 100 150 200 250 300 350 400 450 500
Total Radiation Points

You sprained your ankle —
Get an x–ray and lose a turn
(+1 RP)

Scientific Breakthrough!!
Move ahead 5 spaces

Space walking during sudden flare,
+130 RPs
RETURN TO EARTH

(Only if in space; otherwise ignore)

President endorses program
Move ahead 5 spaces

Comet whizzes by —
Sends you off course, lose a turn
But gain +20 MPs for discovery

(Only if in space; otherwise ignore)

Hit by orbital debris —
repairs needed, lose a turn
Cosmic ray dose +10 RPs

(Only if in space; otherwise ignore)

Congress Budget Subcommittee
cuts funding. GO BACK 3

(Only before launch from Earth;
otherwise ignore)

Claustrophobia sets in
–20 MPs

(Only if in space; otherwise ignore)

Spacecraft charging anomaly
Damage to communication
Loose a turn

(Only if in space; otherwise ignore)

Computer guidance upset
Reboot necessary; lose a turn

(Only if in space; otherwise ignore)

Chance

Chance

Chance

Chance

Chance

Chance

Chance

Chance

Chance

Chance

Discover a Black Hole
You name it after your school
+20 MPs

Observe planets orbiting a distant star +15 MPs

High Scorer on Tetris +5 MPs

Sick of Space Food! –10MPs

UFO rendezvous
You are happy +10 MPs,
but the crew is worried about your health +10RPs

(Only if in space; otherwise ignore)

APPROACHING ASTEROID!
Roll die to see how close it comes:

6 or 5	**Photograph an asteroid +15 MPs**
4 or 3	**Close call! Stress high –10 MPs**
2 or 1	**HIT! You die. Remove your marker from the board**

(Only if in space; otherwise ignore)

Chance

Chance

Chance

Chance

Chance

Chance

Chance

Chance

Chance

Chance

Resources

Learning Technologies, Inc. / Project STAR kits, materials and activities for astronomy	59 Walden St. Cambridge, MA 02140 800–537–8703
Edmund Scientific diffraction gratings, colored filters, lenses, many science materials	N937 Edscorp Bldg. Barrington, NJ 08007 609–573–6250
Astronomical Society of the Pacific books, software, slides, poster, video tapes, newsletter, and 24-hr astronomy hotline	390 Ashton Ave. San Francisco, CA 94112 415–337–2126
Sky Publishing Corp. publishes *Sky and Telescope* magazine; books, sky charts, slides, reprints or activities, videos, etc.	P.O. Box 9111 Belmont, MA 02178–9111 800–253–0245
Roger W. Tuthill, Inc. telescopes, videos, solar filters and Solarskreen™ materials	Box 1086 ST Mountainside, NJ 07092 908–232–1786
Edwin Hirsch, FRAS information on the sun and solar telescope hardware such as Hα filters.	29 Lakeside Dr. Tomkins Cove, NY 10986 914–786–3738
Thousand Oaks Optical carries a large assortment of precision solar filters for telescopes, Hα filters, and mylar filters similar to Solarskreen™	Box 5044–289 Thousand Oaks, CA 91359 805–491–3642
National Geophysical Data Center solar-terrestrial physics data available from a bulletin board system, on CD ROM, on PC floppy disk or a monthly publication	NOAA Code E/GCA, Dept. ORD 325 Broadway Boulder, CO 80303–3328 303–497–6346 Internet: info@ngdc1.colorado.edu BB: 303–497–7319
NASA Headquarters ask for *Programs and Services Summary*, a full list of NASA resources	Educational Affairs Division Washington, DC 20546 202–453–8386
***Science Probe!* Magazine** many ideas for projects that relate to solar-terrestrial interaction that could be adapted to solar projects	500–B Bi County Blvd. Farmingdale, NY 11735 516–293–0467
***Astronomy* Magazine** general astronomy publication and astronomy related products. Forum is available on CompuServe.	Kalmbach Publshing Co. 21027 Crossroads Circle Box 1612 Waukesha, WI 53187 800–533–6644
Black Forest Observatory many educational astronomy products	12815 Porcupine Lane Colorado Springs, CO 80908 719–495–3828

Helmer Enterprises solar viewers and filters	3333 Holy Branch Ct., Suite 453 Sacramento, CA 95834 916–567–0350
Colorado Space Grant Consortium many resource contacts from individuals to clubs to government agencies	University of Colorado at Boulder Campus Box 10 Boulder, CO 80309–0010 303–492–3141
NASA Teacher Resource Center teacher resources for all aspects of space science	AP42 NASA Lyndon B. Johnson Space Center Houston, TX 77058
Martin Marietta Astronautics Group materials related to their current projects	Public Relations Department P.O. Box 179 Denver, CO 80201
Ball Aerospace Systems Group many educational materials, activity packets, slides, etc.	Public Relations Department Boulder, CO 80306 303–939–4410
Science Graphics science teaching slide sets	P.O. Box 7516 Bend, OR 97708 503–389–5652
Tersch Enterprises educational slides on astronomy	P.O. Box 1059 Colorado Springs, CO 80901 719–597–3603
Hansen Planetarium Publications many slides, photos, maps, posters, etc.	1845 South 300 West #A Salt Lake City, UT 84115 801–483–5400
Andromeda Software, Inc. many low cost science programs for a variety of personal computers. Catalog is frequently updated.	P.O. Box 605 Amherst, NY 14226–0605
Zephyr Services computer software and videos related to astronomy	1900 Murray Ave., Dept. A Pittsburgh, PA 15217 800–533–6666
Vernier Software Company computer sensors and probes; data analysis software that could be adapted to projects	2920 S.W. 89th Street Portland, OR 97225 503–297–5317
The Electronics Goldmine electronic parts that could be adapted to solar projects, such as photovoltaic solar cells, and Geiger counter kits for solar flare experiments	P.O. Box 5408 Scottsdale, AZ 85261 602–451–7454
Warner New Media *The View from Earth* CD-ROM for the Mac contains interactive menus on the solar system and the Sun	3500 Olive Ave. Burbank, CA 91505 818–955–9999
Software Marketing Corp. *Orbits* program for the PC (not Windows) contains lots of interactive menus on the solar system and the Sun	9830 S. 51st St. A131 Phoenix, AZ 85044 602–893–2400

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There are many additional excellent books on these subjects. Check your local library.

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Matsushsita, S., and Campbell, W.H., (eds.), *Physics of Geomagnetic Phenomena*, Vols. 1 and 2, International Geophysics Series, Academic Press, NY, 1967.

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Magnetosphere/Ionosphere

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List of Materials

General Supplies

- Tape, glue, rubber bands
- scissors and (or) single-edge razor blades
- grease pencil or water soluble markers
- shoe box
- 3” × 5” note cards
- aluminum foil
- sheet of thin cardboard and of corrugated cardboard
- glass or clear plastic jar with lid
- ruler or meter stick, protractor
- straight pins
- six-sided die

Activity 1

- 2 cm × 2 cm square of holographic or regular diffraction grating
- $^1/_2$ sheet of regular graph paper, 10 squares per cm

optional “The Spectra of the Stars” slide set

optional Preassembled units for spectroscope

Activity 2

- 1 sheet of isometric graph paper

Activity 3

- Thermometer with a range to 50° C
- $^3/_4$” cork stopper with hole for thermometer

Activity 4

- sheet of clear cellophane, about 8 cm square
- 6 cm × 12 cm × 2 cm block of paraffin

Activity 5

- 3 cm × 3 cm squares of colored acetate (or cellophane): red, green, blue
- 3 cm × 3 cm square of Polaroid filter
- 3 cm × 3 cm square of Solarskreen filter

optional “The Sky at Many Wavelengths” slide set and book

Activity 6

- clear hemisphere—plastic or glass—about 15 cm or larger in diameter
- magnetic directional compass

Activity 7

- small bar magnet, about 1 cm $\times$ 1 cm $\times$ 4 cm
- small plane mirror, about 3 cm square
- 30 cm or thin nylon thread
- 20 cm of 20 AWG copper wire

optional pen-sized laser (under $50 from Metrologic Corp.)

Activity 8

- Solar Hα photo set

  or

- *Sky and Telescope* reprint LE 0 14 “Laboratory exercises in Astronomy—the Rotation of the Sun”