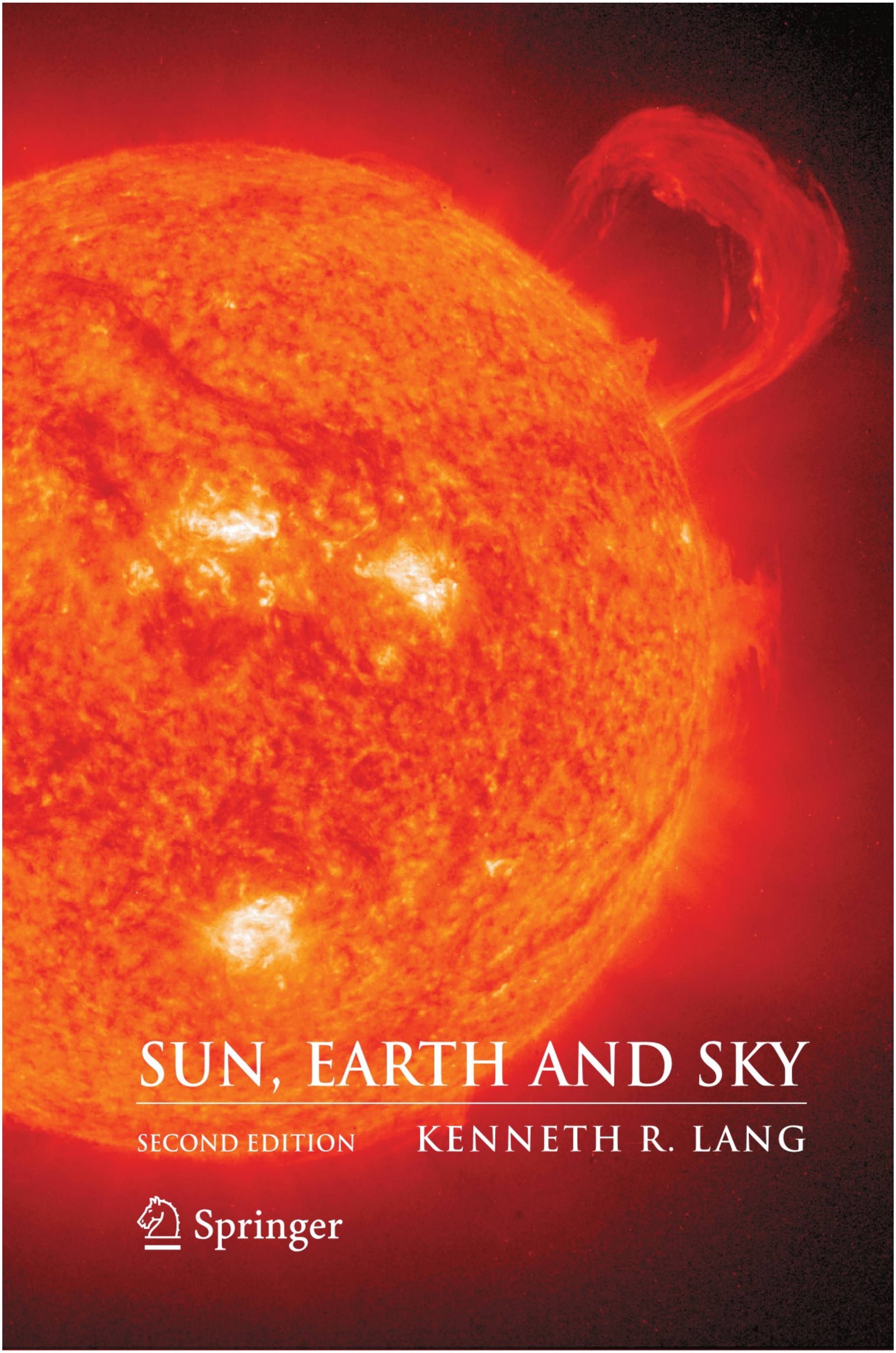

SUN, EARTH AND SKY

SECOND EDITION

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Chapter One

Good Day, Sunshine

WILD GEESE IN SUNLIGHT These geese are flying south in the northern winter, following the Sun's warmth. In this V-shaped pattern of flight, the lead bird deflects currents of air and makes flying easier for those that follow in its wake. The Earth's magnetic field similarly deflects the Sun's wind. (Courtesy of James Tallon.)

1.1 THE RISING SUN

From earliest times, the Sun has been revered and held in awe. For the Greeks of Aristotle's time, sunlight epitomized the fire in the four basic elements – earth, air, fire and water – from which all things arose. Ancient solar observatories, dedicated to the divine Sun-god Ra, can still be found in Luxor, that enchanting city by the Nile; giant Egyptian obelisks, erected thousands of years ago in Luxor and Heliopolis (City of the Sun), now cast their shadows in sundial fashion across parts of Paris, London, and Rome.

According to this incantation from Ptolemaic Egypt:

> Opening his two eyes, [Ra, the Sun god] cast light on Egypt, he separated night from day. The gods came forth from his mouth and mankind from his eyes. All things took their birth from him.[1]

And in the Old Testament's *Book of Genesis,* we find that the Earth was initially a vast waste, covered by darkness, until God said "Let there be light" and the Sun separated day from night.

Since the time of the ancient Persian prophet Zarathustra (about 1300 BC, Greek Zoroaster), we have associated light with good, beauty, truth and wisdom, in sharp contrast with the dark forces of evil. The war between good and evil in the *Dead Sea Scrolls* is depicted as a battle of the Sons of Light against the Sons of Darkness. Dante's divine journey took him from the dark forest to the radiance of paradise, and today we have the evil darkness of Darth Vader in *Star Wars.*

The Maya, Toltec and Aztec of Central America had a host of Sun gods; the Aztecs regularly fed the hearts of sacrificial victims to the Sun to strengthen it on its daily journey. Shintoism, a religion based on Sun worship, has continued for thousands of years in Japan, the land of the rising Sun. Today you can celebrate sunrise with Hindu worshipers on the terraced banks, or ghats, along the Ganges River at Benares, India's holiest city.

Nowadays, fire symbolically lights the darkness in many of our rituals, including the torch of the Olympic games, and candlelight vigils or dimmed lights that bring focus to tragic events and times of crisis. In everyday life, most of us feel happier on bright days than on gloomy ones, so cheerful people have a "sunny" disposition while an unhappy day is a "dark" one. And throughout the world, oiled Sun-worshippers lie on tranquil beaches, letting the summer Sun warm their bodies and give them strength.

The German romantic painter Caspar David Friedrich (1774–1840) used sunrise to portray a spiritual relationship with nature (Fig. 1.1), comparing the "radiating beams of light" in one of his paintings to "the image of the eternal life-giving Father." Sunlight seems to dominate, consume and absorb everything in the paintings of the British artist Joseph Mallord William Turner (1775–1851), who depicted tiny figures dwarfed by the power, beauty and violence of the physical world. When viewing one of his apocalyptic visions, the spectator can become engulfed and lost in the colored light of the sky and sea (Fig. 1.2). The artist's dying words were "The Sun is God."

Examples of artists' perspectives on the Sun are provided at the beginning of every chapter in this book, each chosen for its artistic value and for the new insights

FIG. 1.1 Woman in morning Sun This portrayal of the glowing sunrise by the German artist Caspar David Friedrich (1774–1840) seems to have a transcendental, mystical quality. The painter once compared the "radiating beams of light" in one of his paintings to "the image of the eternal life-giving Father." (Courtesy of Museum Folkwang, Essen.)

it offers. Here you will find "another light, a stronger Sun" portrayed by the Dutch painter Vincent Van Gogh (1853–1890), who used thick brush stokes of blazing, brilliant pigment, as dense as honey, to portray a powerful, yellow Sun that blazes forth with an almost supernatural radiance. The French artist Claude Monet's (1840–1926) painting of sunrise is included – the one that inaugurated the impressionist movement of painting. He used entire sequences of paintings to depict the subtle changes that varying sunlight causes in our perception of objects, such as haystacks or the cathedral at Rouen.

The chapter frontispieces also include the works of the Spanish painter Joan Miró (1893–1983), who portrayed the powerful red disk of the Sun that caresses our limbs and brings us joy, or links us to the stars beyond. In other instances, we reproduce works that separate the Sun from any reference to the Earth or sky; they show that the Sun can be an intense source of pleasure and beauty by itself.

Writers have also been captivated by the light of the Sun, from the American author Ralph Waldo Emerson (1803–1882), who wrote that pure light was "the reappearance of the original soul," to the German philosopher Friedrich Nietzsche (1844–1900) who wrote in *Thus Spoke Zarathustra:*

> The Moon's love affair has come to an end!
> Just look! There it stands; pale and dejected – before the dawn!

FIG. 1.2 **Regulus** In this painting by the British artist Joseph Mallord William Turner (1775–1851), every object is in a fiery, misty state. Brilliant yellow rays of light come down from a central, all-powerful Sun, absorbing and consuming everything else. The picture is named after the Roman general Regulus who was punished for his betrayal of the Carthaginians by having his eyelids cut off, and being blinded by the glare of the Sun. Regulus, who is apparently absent from the scene, has been identified with the spectator, staring into the blinding Sun. (Courtesy of the Tate Gallery, London.)

> For already it is coming, the glowing Sun –
> *its* love of the Earth is coming!
> All Sun-love is innocence and creative desire!
> Just look how it comes impatiently over the sea!
> Do you not feel the thirst and hot breath of its love?[2]

The Sun warms our soul, and lights and heats our days! Today's astronomers may describe the Sun, and our dependence upon it, in greater scientific detail than artists or writers, but that in no way diminishes their sense of awe for the life-sustaining, even mystical power of the Sun.

1.2 FIRE OF LIFE

The Sun is our powerhouse. It energizes our planet, warming the ground and lighting our days. It is solar heat that powers the winds and cycles water from sea to rain, the source of our weather and arbiter of our climate. And the Sun is the source of the energy that sustains life.

Without its heat and light, all life would quickly vanish from the surface of our planet. And the Sun provides – directly or indirectly – most of our energy. Green plants absorb sunlight where it strikes chlorophyll, giving them the energy to break water molecules apart and energize photosynthesis; plants thereby use the Sun's energy to live and grow, giving off oxygen as a byproduct (Fig. 1.3). Eating these plants nourishes animals. And long-dead, compressed plants provide the petroleum, coal or natural gas that energizes the lights in your house or powers the car you drive.

The Earth glides through space at just the right distance from the Sun for life to thrive on our planet's surface, while other planets freeze or fry. We sit in the comfort

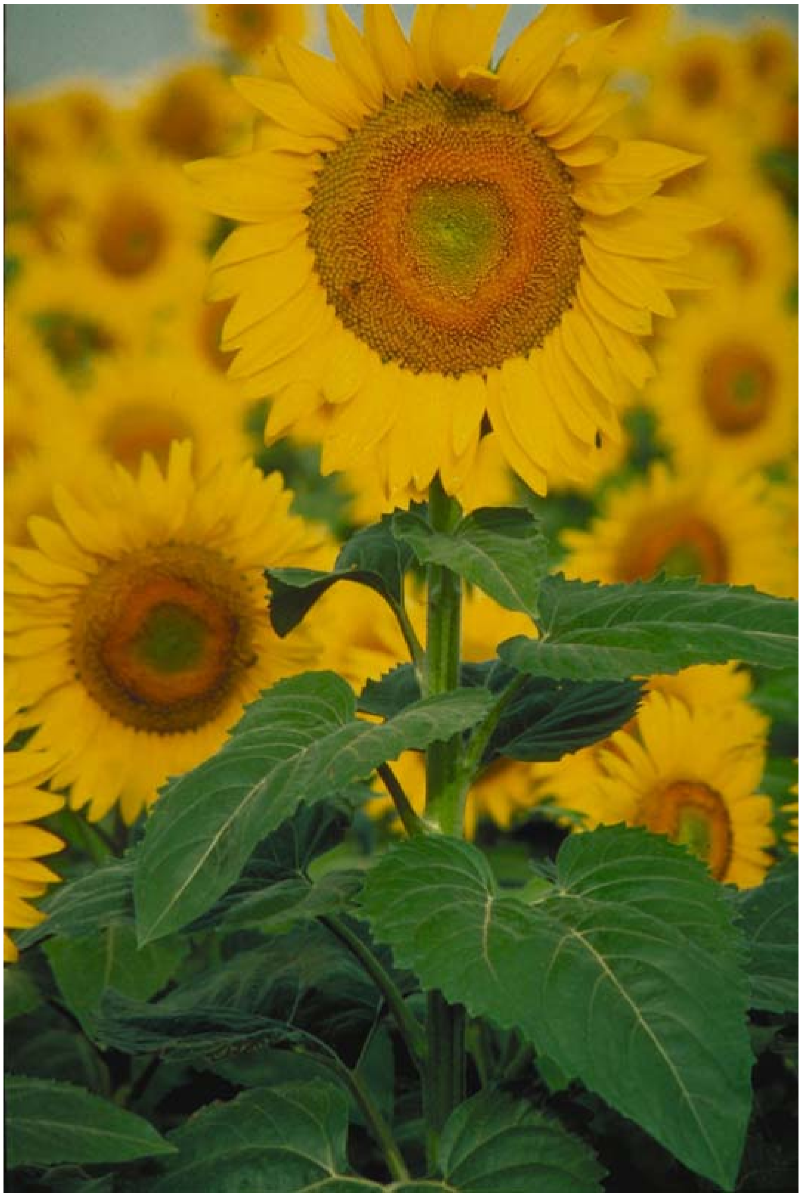

FIG. 1.3 Sunflowers The Sun sustains all living creatures and plants on Earth. Green plants absorb sunlight, giving them the energy to break water molecules apart and energize photosynthesis. Plants thereby use the Sun's energy to live and grow, giving off oxygen as a byproduct. (Courtesy of Charles E. Rodgers.)

zone. Any closer and the oceans would boil away. Further out the Earth would be a frozen wasteland.

We receive just enough energy from the Sun to keep most of our water liquid, which is a requirement for life, as we know it. In comparison, the surface of Venus, just slightly closer to the Sun, is hot enough to melt lead; further away from the Sun, the planet Mars is now frozen into a global ice age. It cannot now rain on Mars, and any liquid water released on its surface will either evaporate or freeze into ice. Turn off the Sun's powerhouse, and in just a few months we could all be under ice.

1.3 SUNLIGHT

Occasionally the mixture of colors in a beam of sunlight is spread before our eyes, as when raindrops act like tiny prisms, bending white sunlight into its separate colors and giving us a rainbow (Fig. 1.4). Our eyes and brain translate the visible sunlight into colors. From long to short waves, they correspond to red, orange, yellow, green, blue and violet. Plants appear green, for example, because they absorb red sunlight and reflect the green portion of the Sun's light.

However, your world might be colored somewhat differently from someone else's. There are subtle differences in the exact shade of color we perceive, depending on the molecules in our eye's detection system. So, even people with normal eyesight do not always see eye to eye.

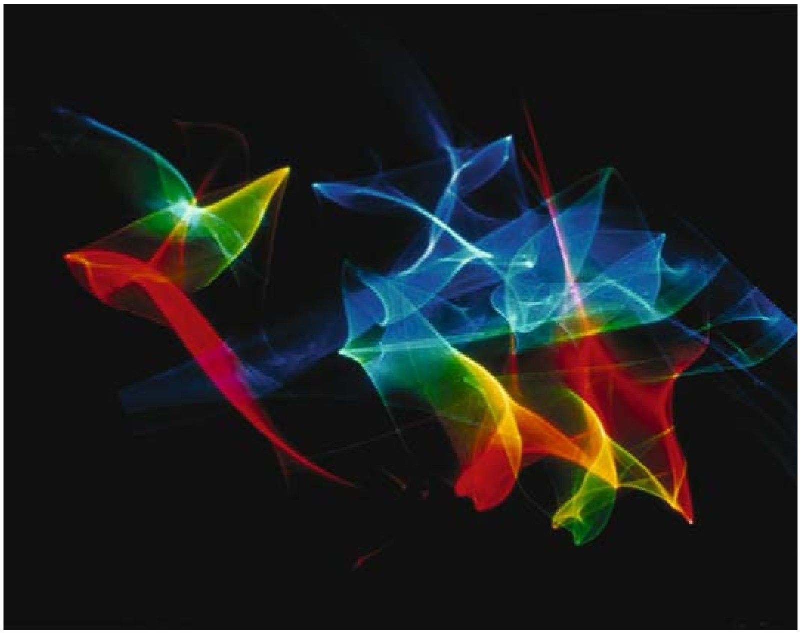

FIG. 1.4 Light painting This picture was made by using crystals to liberate the spectral colors in visible sunlight, refracting them directly onto a photographic plate. It was obtained in the rarefied atmosphere atop Hawaii's Mauna Kea volcano, where many of the world's best telescopes are located. (Courtesy of Eric J. Pittman, Victoria, British Colombia.)

The most intense radiation of the Sun is emitted at the visible wavelengths of colored light, and our atmosphere permits them to reach the ground. If our eyes were not so sensitive to visible sunlight, we could not identify objects or move around on the Earth's surface. Thus, the sensitivity of our eyes is matched to the tasks of vision.

The Sun also emits invisible radiation, with less intensity than the visible sort. In 1800, for example, the German-born English astronomer William Herschel (1738–1822) discovered invisible radiant heat, or infrared radiation, by noticing a rise in temperature when a thermometer is placed beyond the red end of the visible spectrum of sunlight.

We all glow in the dark, emitting infrared radiation. You can't see anyone's infrared heat radiation, it's outside your range of vision, but you can feel it. In contrast, rattlesnakes have infrared-sensitive eyes that enable them to see the heat radiated by animals at night, and the military uses infrared technology to sense and locate the heat generated by the enemy in the total dark. Night-vision gobbles with infrared sensors are an example.

The Sun also emits invisible ultraviolet radiation, radio waves and X-rays, which differ in the length of their waves. X-rays are very short, much smaller than the ultraviolet whose waves are just a little smaller than those of blue sunlight, and radio waves that are very long. The properties of these different types of the Sun's radiation are described in Section 1.8.

1.4 DAYTIME STAR

All stars are suns, kin to our own daytime star. Indeed, the Sun is just one of about one hundred billion stars in our Galaxy, the Milky Way, and countless billions of galaxies stretch out in the seemingly boundless Universe. But the Sun is a special star; it is our only daytime star! Nothing else in the Universe is so critically important to us. As the Victorian English poet Francis William Bourdillon (1852–1921) wrote:

> The night has a thousand eyes,
> And the day but one;
> Yet the light of the bright world dies,
> With the dying Sun.
>
> The mind has a thousand eyes,
> And the heart but one:
> Yet the light of a whole life dies
> When love is done[3]

The Sun is a quarter million times closer to us than the next nearest star. Because of this closeness, the Sun is about a hundred billion times brighter than any other star. The Sun's brilliance provides ample light for the most exacting studies of its chemical constituents, magnetic fields, and oscillations. This blessing can also be a curse, for the Sun's heat can melt mirrors or burn up electronic equipment when focused to high intensity. For this reason, special mirror configurations are used to reduce the concentration of visible sunlight, while still producing large images that contain fine detail (Fig. 1.5).

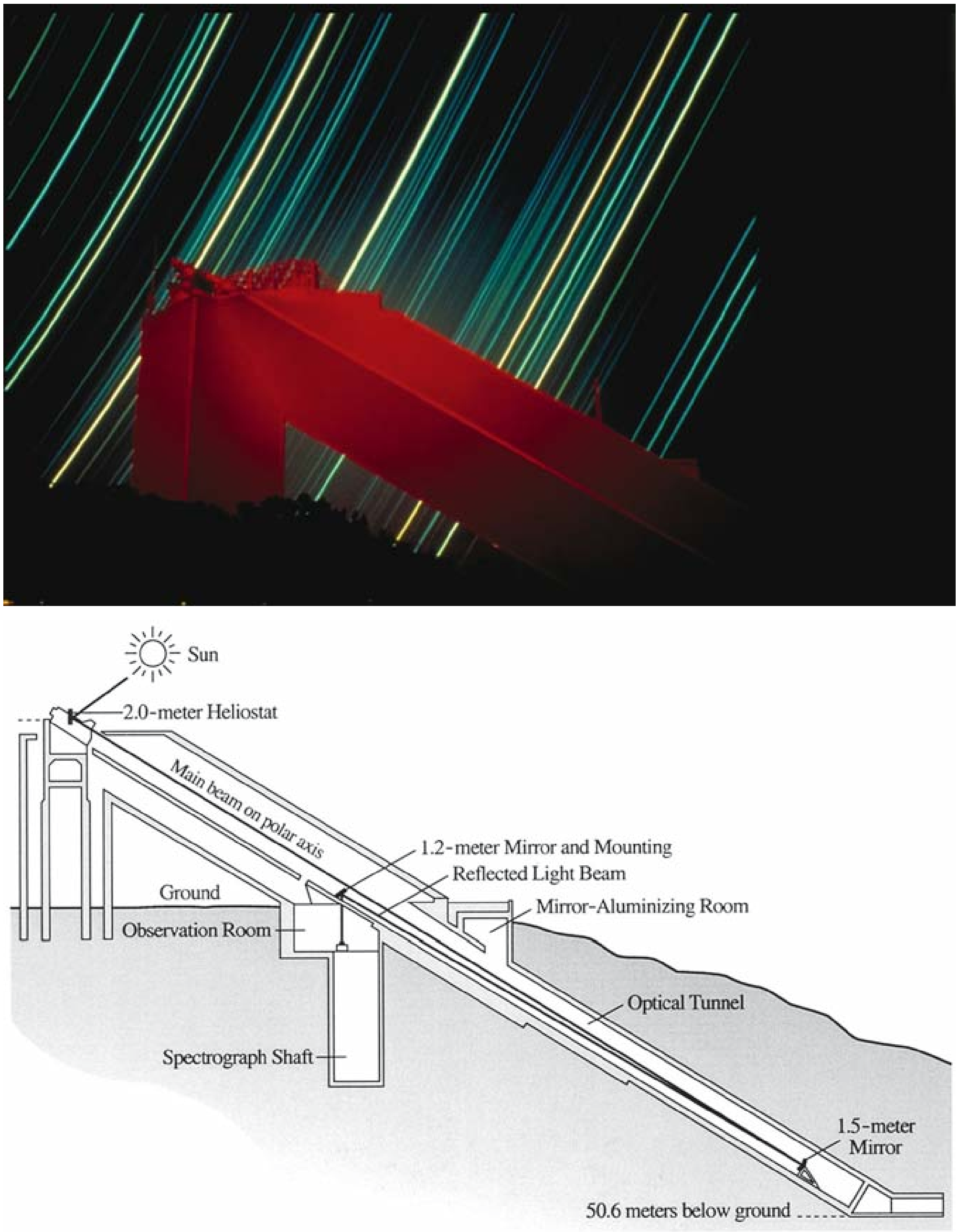

FIG. 1.5 Eyes on the Sun Scattered sunlight colors the McMath solar telescope a stunning red, while stars mark trails across the evening sky *(top)*. A moveable heliostat, perched atop this telescope, follows the Sun and directs its light downward through the long fixed shaft of the telescope (*bottom*). A figured mirror at the shaft bottom reflects and focuses the sunlight toward the observation room. The shaft's axis is parallel to the rotation axis of the Earth, and about three fifths of it is underground. It is kept cool by pumping cold water through tubes in the exterior skin, thereby reducing turbulence in the air inside and keeping the Sun's image steady. (Courtesy of William C. Livingston, NOAO.)

The Sun's proximity allows a level of detailed examination unique among stars. While most other stars appear only as unresolved spots of light in the best telescopes, the Sun reveals its features in exquisite detail. Most ground-based optical telescopes can resolve structures on the Sun's visible disk that are about 750 kilometers across, about the distance from Boston to Washington, D.C. and about three-quarters the size of France; that is comparable to seeing the details on a coin from one kilometer away.

Yet, the resolution of ground-based telescopes is limited by turbulence in the Earth's atmosphere; it reduces the clarity of the Sun's image at visible wavelengths. Similar variations cause the stars to twinkle at night. The best visible images with even finer detail can be obtained using adaptive optics that correct for the changing atmosphere, or from the unique vantage point of outer space using satellite-borne telescopes unencumbered by the limits of our atmosphere.

The other stars are so far away that their surfaces remain unresolved with even the largest telescopes. The Sun therefore permits examination of physical phenomena and processes that cannot be seen in detail on other stars. Furthermore, the Sun's basic properties provide benchmarks and boundary conditions for the study of stellar structure and evolution.

So, all astronomers do not work in the dark. Many of them closely scrutinize our daytime star, deciphering some of the most fundamental secrets of nature.

1.5 COSMIC LABORATORY

The Sun can be a site to test physical theories under conditions not readily attainable in terrestrial laboratories. For example, in contrast to our material world, the Sun's core also contains small quantities of short-lived anti-matter. When subatomic matter and anti-matter collide, they destroy each other, releasing pure radiative energy. We can also detect the process during explosions on the visible solar disk, which briefly become hotter than the center of the Sun.

Other particles made deep inside our home star pass effortlessly through both the Sun and the Earth. Recent observations of these ghostlike neutrinos have helped us understand the subatomic realm at levels beyond the reach of today's most powerful particle accelerators, providing new insight to a theory that might someday unify all the forces of nature.

From afar, the Sun seems to be calm, serene, and unchanging, a steadily shining beacon in the sky; but detailed observations reveal an active, ever-changing Sun. Violent storms and explosive eruptions create gusts in its steady flow of heat, particles and light. The Sun therefore provides us with a unique, high-resolution perspective of the perpetual change and violent activity that characterize much of the Universe.

Thus, we now understand the Sun as a unique star, one so close that it serves as a cosmic laboratory for understanding the physical processes that govern all the other stars, as well as the entire Universe. Everything we learn about the Sun has implications throughout the Cosmos, including planet Earth. As examples, observations of the Sun's visible radiation unlocked the chemistry of the Universe, and investigations of the Sun's internal furnace paved the way to nuclear energy.

1.6 INGREDIENTS OF THE SUN

Celestial objects are composed, like the Earth and we ourselves, of individual particles of matter called atoms. But the atoms consist largely of seemingly empty space, just as the room you may be sitting in appears mostly empty. A tiny, heavy, positively charged nucleus lies at the heart of an atom, surrounded by a cloud of relatively minute, negatively charged electrons that occupy most of an atom's space and govern its chemical behavior.

In the early 20th century, the New Zealand-born British physicist Ernest Rutherford (1871–1937) showed that radioactivity is produced by the disintegration of atoms, and discovered that they emit energetic alpha particles, which consist of helium nuclei; he was awarded the 1908 Nobel Prize in Chemistry for these achievements. By using helium ions to bombard atoms, Rutherford was able to announce in 1911 that most of the mass of an atom is concentrated in a nucleus that is 100,000 times smaller than the atom and has a positive charge balanced by the negative charge of surrounding electrons.

Nearly a decade later, in 1920, Rutherford announced that the massive nuclei of all atoms are composed of hydrogen nuclei, which he named protons. He also postulated the existence of an uncharged nuclear particle, later called the neutron, which was required to help hold the nucleus together and keep it from dispersing as the protons repelled each other. After an eleven-year search, the English physicist James Chadwick (1891–1974) discovered the neutron, in 1932, receiving the 1935 Nobel Prize in Physics for the feat. So, the nucleus of an atom is composed of positively charged protons and neutral particles, called neutrons; both about 1,840 times heavier than the electron.

The simplest and lightest atom consists of a single electron circling around a nucleus composed of a single proton without any neutrons; this is an atom of hydrogen. The nucleus of helium, another abundant light atom, contains two neutrons and two protons, and the helium atom therefore has two electrons.

The atomic ingredients of the Sun can be inferred from dark absorption lines, which are found superimposed on the colors of sunlight (Fig. 1.6). They look like a dark line when the Sun's radiation intensity is displayed as a function of wavelength; such a display is called a spectrum. The term Fraunhofer absorption line is also used, recognizing the German astronomer Joseph von Fraunhofer (1787–1826). By directing the incoming sunlight through a slit, and then dispersing it with a prism, Fraunhofer was able to overcome the blurring of colors from different parts of the Sun's disk, discovering numerous dark absorption lines. By 1814 he had detected and catalogued more than 300 of them, assigning Roman letters to the most prominent.

The Sun is so bright that its light can be spread out into very small wavelength intervals with enough intensity to be detected. The instrument used to make and record such a spectrum is called a spectrograph, a composite word consisting of *spectro* for "spectrum" and *graph* for "record". The spectrograph spreads out the wavelengths into different locations, as a rainbow or prism does. Nowadays it is the grooves of a diffraction grating that reflect sunlight into different locations according to color or wavelength. And you can see such a colored display by looking at a compact disk.

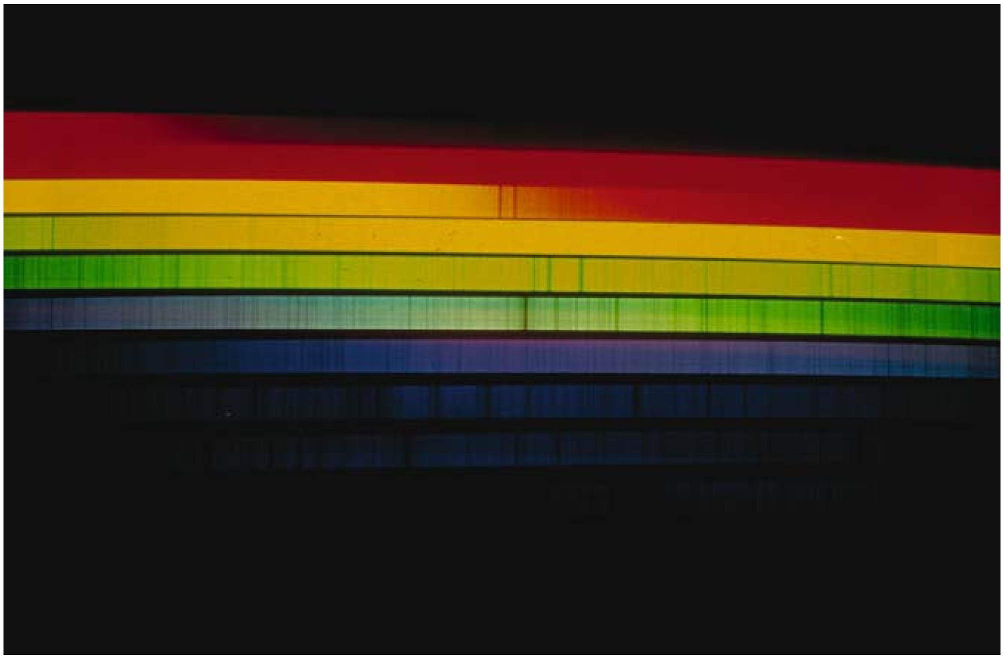

FIG. 1.6 Visible solar spectrum A spectrograph has spread out the visible portion of the Sun's radiation into its spectral components, displaying radiation intensity as a function of wavelength. When we pass from long wavelengths to shorter ones (*left* to *right, top* to *bottom*), the spectrum ranges from red through orange, yellow, green, blue and violet. Dark gaps in the spectrum, called Fraunhofer absorption lines, are due to absorption by atoms in the Sun. The wavelengths of these absorption lines can be used to identify the elements in the Sun, and the relative darkness of the lines helps establish the relative abundance of these elements. (Courtesy of National Solar Observatory, Sacramento Peak, NOAO.)

When a cool, tenuous gas is placed in front of a hot, dense one, atoms in the cool gas absorb radiation at specific wavelengths, thereby producing dark absorption lines. And when a tenuous gas stands alone and is heated to incandescence, emission lines are produced that shine at precisely the same wavelengths as the dark ones. The Sun's dark absorption lines and bright emission lines carry messages from inside the atom, and help us determine its internal behavior.

Adjacent lines of the hydrogen atom exhibit a strange regularity – they systematically crowd together and become stronger at shorter wavelengths. The Swiss mathematics teacher Johann Balmer (1825–1898) published an equation that describes the regular spacing of the wavelengths of the four lines of hydrogen detected in the spectrum of visible sunlight, and they are still known as Balmer lines. The strongest one, with a red color, is also called the hydrogen alpha line.

In 1913, the Danish physicist Niels Bohr (1885–1962) explained Balmer's equation by an atomic model, now known as the Bohr atom, in which the single electron in a hydrogen atom revolves about the nuclear proton in specific orbits with definite, quantized values of energy. An electron only emits or absorbs radiation when jumping between these allowed orbits, each jump being associated with a specific energy and a single wavelength, like one pure note. If an electron jumps from a low-energy orbit to a high-energy one, it absorbs radiation at this wavelength; radiation is emitted at exactly the same wavelength when the electron jumps the opposite way. This unique wavelength is related to the difference between the two orbital energies. Bohr was awarded the 1912 Nobel Prize in Physics for his investigations of the structure of atoms and the radiation emanating from them.

Since only quantized orbits are allowed, spectral lines are only produced at specific wavelengths that characterize or identify the atom. An atom or molecule can absorb or emit a particular type of sunlight only if it resonates to that light's energy. As it turns out, the resonating wavelengths or energies of each atom are unique – they fingerprint an element, encode its internal structure and identify the ingredients of the Sun. In addition, spectral lines yield information about the Sun's temperature, density, motion and magnetism.

Each element, and only that element, produces a unique set of absorption or emission lines. The presence of these spectral signatures can therefore be used to specify the chemical ingredients of the Sun (Fig. 1.7). The abundance calculations depend upon both measurements of the solar lines and on properties of the elements detected in the terrestrial laboratory. The lightest element, hydrogen, is the most abundant element in the Sun and most other stars (Focus 1.1). Altogether, 92.1 percent of the atoms in the Sun are hydrogen atoms, 7.8 percent are helium atoms, and all the other heavier

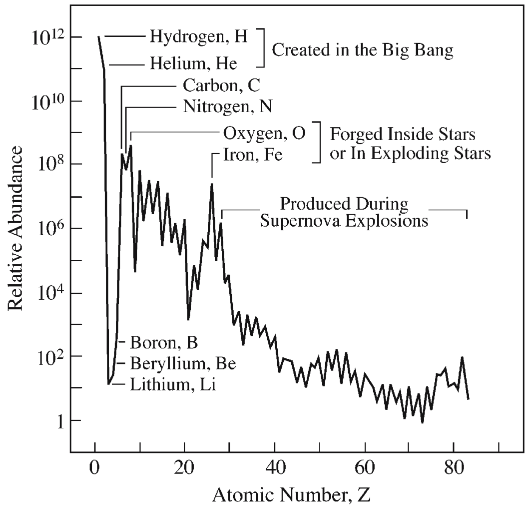

FIG. 1.7 Abundance and origin of the elements in the Sun The relative abundance of the elements in the solar photosphere, plotted as a function of their atomic number, Z. The abundance is specified on a logarithmic scale and normalized to a value a million, million, or 1.0×10^{12}, for hydrogen. Hydrogen, the lightest and most abundant element in the Sun, was formed about 14 billion years ago in the immediate aftermath of the Big Bang that led to the expanding Universe. Most of the helium now in the Sun was also created then. All the elements heavier than helium were synthesized in the interiors of stars that no longer shine, and subsequently wafted or blasted into interstellar space where the Sun originated. Carbon, nitrogen, oxygen and iron, were created over long time intervals during successive nuclear burning stages in former stars, and also during the explosive death of massive stars. Elements heavier than iron were produced by neutron capture reactions during the supernova explosions of massive stars that lived and died before the Sun was born. The atomic number, Z, is the number of protons in the nucleus, or roughly half the atomic weight. The elements shown, He, C, N, O and Fe, have Z = 2, 6, 7, 8 and 26, with atomic weights of 4, 12, 14, 16, and 56, since each nucleus contains as many neutrons as protons with about the same weight. Hydrogen has one proton and no neutrons in its nucleus. The exponential decline of abundance with increasing atomic number and weight can be explained by the rarity of stars that have evolved to later stages of life. (Data courtesy of Nicolas Grevesse.)

FOCUS 1.1
Composition of the Stars

In the mid-nineteenth century, the German physicist Gustav Kirchhoff (1824–1887) discovered a method for determining the ingredients of the stars. Working with the German chemist Robert Bunsen (1811–1899), Kirchhoff showed that every chemical element, when heated to incandescence, emits brightly colored spectral signatures, or emission lines, whose unique wavelengths coincide with those of the dark absorption lines in the Sun's spectrum.

By comparing the Sun's absorption lines with emission lines of elements vaporized in the laboratory, Kirchhoff identified in the solar atmosphere several elements known on Earth, including sodium, calcium and iron. This suggested that stars are composed of terrestrial elements that are vaporized at the high stellar temperatures, and it unlocked the chemistry of the Universe. As Bunsen wrote in 1859:

> At the moment I am occupied by an investigation with Kirchhoff, which does not allow us to sleep. Kirchhoff has made a totally unexpected discovery, inasmuch as he has found out the cause for the dark lines in the solar spectrum and can produce these lines artificially intensified both in the solar spectrum and in the continuous spectrum of a flame, their position being identical with that of Fraunhofer's lines. Hence the path is opened for the determination of the chemical composition of the Sun and the fixed stars.[4]

In a brilliant doctoral dissertation, published in 1925, the American astronomer Cecilia H. Payne (1900–1979) showed that the atmospheres of virtually every luminous, middle-aged star have the same ingredients. Miss Payne, later Payne-Gaposchkin, eventually became the first female Professor in the Faculty of Arts and Sciences at Harvard University, where she had studied. Her calculations also indicated that hydrogen is by far the most abundant element in the Sun and most other stars. But she could not believe that the composition of stars differed so enormously from that of the Earth, where hydrogen is rarely found, so she mistrusted her understanding of the hydrogen atom. Prominent astronomers of the time also did not think that hydrogen was the main ingredient of the Sun and other stars, and this may have played a role in her considerations.

We now know that hydrogen is the most abundant element in the Universe, and that there was nothing wrong with Miss Payne's calculations. The Earth just does not have sufficient gravity to retain hydrogen in its atmosphere. Any hydrogen gas that our planet might have once had must have evaporated away while the Earth was forming and has long since escaped.

Subsequent observations have shown that very old stars have practically no elements other than hydrogen and helium; these stars have probably existed since our Galaxy formed. Middle-aged stars like the Sun contain heavier elements. They must have formed from the ashes of previous generations of stars that have fused lighter elements into heavier ones.

The Sun is mainly composed of light elements, hydrogen and helium, which are terrestrially rare, whereas the Earth is primarily made out of heavy elements that are relatively uncommon in the Sun (Table 1.1). Hydrogen is about one million times more abundant than iron in the Sun, but iron is one of the main constituents of the Earth, which cannot even retain hydrogen gas in its atmosphere.

elements make up only 0.1 percent. In contrast, the main ingredients of the rocky Earth are the heavier elements like silicon and iron, and this explains the Earth's higher mass density – about four times that of the Sun, which is only about as dense as water.

Helium, the second-most abundant element in the Sun, is so rare on Earth that it was first discovered on the Sun – by the French astronomer Pierre Jules Janssen

TABLE 1.1 The twenty most abundant elements in the solar photosphere

Element	Symbol	Atomic Number	Abundance[a] (logarithmic)	Date of Discovery on Earth
Hydrogen	H	1	12.00	1766
Helium	He	2	[10.93 ± 0.01]	1895[b]
Carbon	C	6	8.39 ± 0.05	(ancient)
Nitrogen	N	7	7.78 ± 0.06	1772
Oxygen	O	8	8.66 ± 0.05	1774
Neon	Ne	10	[7.84 ± 0.06]	1898
Sodium	Na	11	6.17 ± 0.04	1807
Magnesium	Mg	12	7.53 ± 0.09	1755
Aluminum	Al	13	6.37 ± 0.06	1827
Silicon	Si	14	7.51 ± 0.04	1823
Phosphorus	P	15	5.36 ± 0.04	1669
Sulfur	S	16	7.14 ± 0.05	(ancient)
Chlorine	Cl	17	5.50 ± 0.30	1774
Argon	Ar	18	[6.18 ± 0.08]	1894
Potassium	K	19	5.08 ± 0.07	1807
Calcium	Ca	20	6.31 ± 0.04	1808
Chromium	Cr	24	5.64 ± 0.10	1797
Manganese	Mn	25	5.39 ± 0.03	1774
Iron	Fe	26	7.45 ± 0.05	(ancient)
Nickel	Ni	28	6.23 ± 0.04	1751

[a] Logarithm of the abundance in the solar photosphere, normalized to hydrogen = 12.00, or an abundance of 1.00×10^{12}. Indirect solar estimates are marked with [ ]. The data are courtesy of Nicolas Grevesse, Université de Liège.

[b] Helium was discovered on the Sun in 1868, but it was not found on Earth until 1895.

(1824–1907) and the British astronomer Joseph Norman Lockyer (1826–1920) as emission lines observed during the solar eclipse of 18 August 1868. Since it seemed to be only found on the Sun, Lockyer named it after the Greek Sun god, Helios, who daily traveled across the sky in a chariot of fire drawn by four swift horses. In 1895, while analyzing a gas given off by a heated uranium mineral, the Scottish chemist William Ramsay (1852–1916) found the spectral signature of helium, thereby isolating it on the solid Earth 27 years after its discovery in the Sun.

Today, helium is used on Earth in a variety of ways, including inflating party balloons and in its liquid state keeping sensitive electronic equipment cold. But there isn't much helium left on the Earth, and we are in danger of running out of it soon.

1.7 CHILDREN OF THE COSMOS

We are made of the same atoms as the Sun. Our bodies, like the Sun, have more hydrogen atoms than any other, but we are composed of a somewhat larger proportion of heavier elements like carbon, nitrogen, and oxygen.

But do not discount the other stars. We are all true children of the stars, partially composed of materials that were forged within ancient stars before the Sun was born. All of the elements heavier than helium were generated long, long ago and far, far away in the nuclear crucibles of other stars, which lit up the night sky and were extinguished before the Solar System came into being.

These stars used up their internal fuel and spewed out their cosmic ashes with explosive force, ejecting the heavier elements into interstellar space. From this recycled material, the Sun, the Earth and we ourselves were formed. So, the carbon in your molecules, the calcium in your teeth, the oxygen in your water and the iron that reddens your blood all came from the interiors of other stars, long since exploded back into space in the death throes of these stars.

But all the hydrogen in the Earth's water and in your body, as well as all of the hydrogen in the stars and most of their internal helium, was synthesized about 14 billion years ago, in the Big Bang that jump-started the expanding Universe. We are thus children of both the stars that exploded during past eons and the Big Bang at the beginning of time.

1.8 DESCRIBING THE RADIATION

The Sun continuously radiates energy that spreads throughout space. This radiation is called "electromagnetic" because it propagates by the interplay of oscillating electrical and magnetic fields in space. Electromagnetic waves all travel through empty space at the same constant speed – the velocity of light. This velocity is usually denoted by the lower case letter c, and it has a value of roughly 300,000 kilometers per second – a more exact value is 299,793 kilometers per second. No energy can be transported more swiftly than this speed of light.

Sunlight has no way of marking time, and it can persist forever. As long as a ray of sunlight passes through empty space and encounters no atoms or electrons it will survive unchanged. Radiation emitted from the Sun today might therefore travel for all time in vacuous space, bringing its message forward to the end of the Universe.

Some of the radiation streaming away from the Sun is nevertheless intercepted at Earth, where astronomers describe it in terms of its wavelength, frequency, or energy. When light propagates from one place to another, it often seems to behave like waves or ripples on a pond (Fig. 1.8). The light waves have a characteristic wavelength, the separation between adjacent wave crests.

Different types of electromagnetic radiation differ in their wavelength (Fig. 1.9), although they propagate at the same speed. The electromagnetic waves entering your eye and those picked up by your radio antenna or used to X-ray your bones are similar except in relation to their wavelength.

X-rays are much smaller than an atom, with wavelengths that are between 10^{-11} and 10^{-8} meters long, and because of this small size, cosmic X-rays are totally absorbed

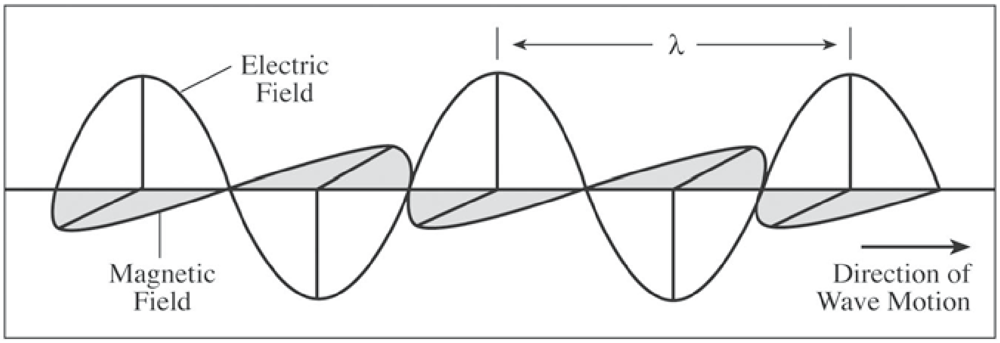

FIG. 1.8 Electromagnetic waves All forms of radiation consist of electric and magnetic fields that oscillate at right angles to each other and to the direction of travel. They move through empty space at the velocity of light. The separation between adjacent wave crests is called the wavelength of the radiation and is often designated by the lower case Greek letter lambda or λ.

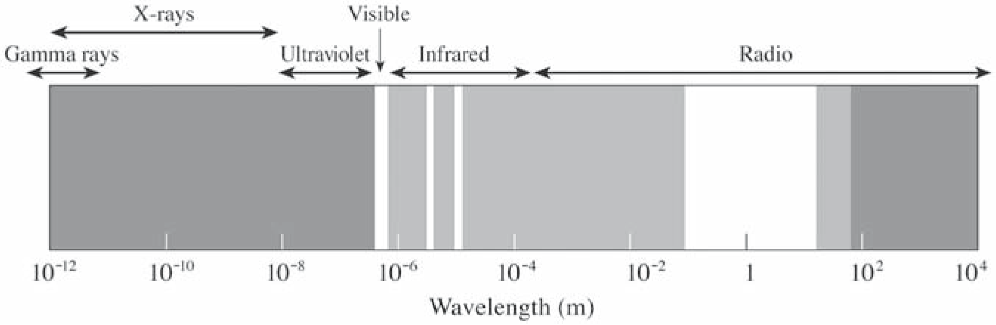

FIG. 1.9 Electromagnetic spectrum Radiation from the Sun and other cosmic objects is emitted at wavelengths from less than 10^{-12} meters to greater than 10^4 meters. The visible spectrum is a very small portion of the entire range of wavelengths. The lighter the shading, the greater the transparency of the Earth's atmosphere. Solar radiation only penetrates to the Earth's surface at visible and radio wavelengths, respectively denoted by the narrow and broad white areas. Electromagnetic radiation at short X-ray and ultraviolet wavelengths, represented by the dark areas at the left, is absorbed in our air, so the Sun is now observed in these spectral regions from above the atmosphere in Earth-orbiting satellites.

in our atmosphere, never reaching the ground. The wavelength of ultraviolet radiation, which is also absorbed in our air, is just a bit longer, between 10^{-8} and 10^{-7} meters, with extreme ultraviolet radiation lying in the short wavelength part of this range. In contrast radio waves are between 0.001 and 30 meters long. So radio waves can be as big as you are tall, or even as large as a house or skyscraper, too long to enter the eye and not energetic enough to affect vision.

Just as a source of sound can vary in pitch, or wavelength, depending on its motion, the wavelength of electromagnetic radiation shifts when the object emitting or reflecting the radiation moves with respect to the observer (Fig. 1.10). This is called the Doppler effect, after the Austrian physicist Christian Johann Doppler (1803–1853), who discovered it in 1842. If the motion is toward the observer, the Doppler effect

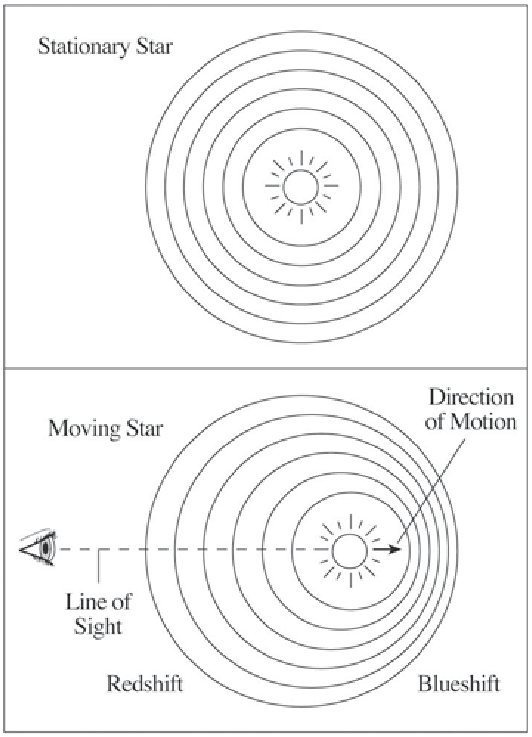

FIG. 1.10 Doppler effect A stationary star (*top*) emits regularly spaced light waves that get stretched out or scrunched up if the star moves (*bottom*). Here we show a star moving away (*bottom right*) from the observer (*bottom left*). The stretching of light waves that occurs when the star moves away from an observer along the line of sight is called a redshift, because red light waves are relatively long visible light waves; the compression of light waves that occurs when the star moves along the line of sight toward an observer is called a blueshift, because blue light waves are relatively short. The wavelength change, from the stationary to moving condition, is called the Doppler shift, and its size provides a measurement of radial velocity, or the velocity of the component of the star's motion along the line of sight. The Doppler effect is named after the Austrian physicist Christian Doppler (1803–1853), who first considered it in 1842.

shifts the radiation to shorter wavelengths, and when the motion is away the wavelength becomes longer. Such an effect is responsible for the change in the pitch of a passing ambulance siren. Because everything in the Universe moves, the Doppler effect is a very important tool for astronomers; it measures the velocity of that motion along the line of sight to the observer.

Sometimes radiation is described by its frequency instead of its wavelength. Radio stations are, for example, denoted by their call letters and the frequency of their broadcasts, usually in units of a million cycles per second, or megahertz, for FM broadcasts.

The frequency of a wave is the number of crests passing a stationary observer each second; the frequency therefore tells us how fast the radiation oscillates, or moves up and down. The product of wavelength and frequency equals the velocity of light, so when the wavelength increases the frequency decreases and *vice versa.*

When light is absorbed or emitted by atoms, it behaves like packages of energy, called photons, which can be created or destroyed. The photons are produced whenever a material object emits electromagnetic radiation, and they are consumed when matter absorbs radiation. Radiation therefore disappears and ceases to exist when absorbed by matter. But energy is neither created nor destroyed; it is just removed from the radiation.

Moreover, each elemental atom can only absorb and emit photon energy in specific amounts. This is a consequence of the unique arrangement of electrons in each atom, and the pattern of photon energy emitted and absorbed can therefore be used to identify the atom.

At the atomic level, the natural unit of energy is the electron volt, abbreviated eV. One electron volt is the energy an electron gains when it passes across the terminals of a 1-volt battery. A photon of visible light has an energy of about two electron volts, or 2 eV. Much higher energies are associated with nuclear processes; they are often specified in units of millions of electron volts, or MeV for short. A somewhat lower unit of energy is a thousand electron volts, called the kilo-electron volt or keV; it is often used to describe X-ray radiation.

The interaction of each type of radiation with matter depends on the energy of its photons, and from the standpoint of the astrophysicist this is the most important property distinguishing one type of radiation from another. In fact, astronomers often describe energetic radiation, such as X-rays or gamma rays, in terms of its energy rather than its wavelength or frequency.

Photon energy is inversely proportional to the wavelength and directly proportional to the frequency. Radiation with a shorter wavelength or a higher frequency therefore corresponds to photons with higher energy. Radio photons have relatively long wavelengths and low frequencies, so they have less energy than the short-wavelength, high frequency X-ray radiation. The low energies of radio photons cannot easily excite the atoms of our atmosphere, so these photons easily pass through the air, even in stormy weather. In contrast, X-rays are totally absorbed when traveling just a short distance through the atmosphere. The energetic X-rays produced by machines here on Earth pass right through your skin, muscles, or teeth. It also takes much less energy to broadcast a radio signal over short distances than to take an X-ray of a broken bone.

The energy of stellar radiation at a given wavelength can be related to the thermal energy, or the temperature, of the emitting gas. Hot stars tend to be bluer in color, for example, and colder stars are redder. This is because the most intense emission occurs at a radiation frequency and energy that increase with the temperature of the star's visible disk. In other words, the emitted power peaks out at a wavelength that varies inversely with the temperature, and this applies to all gaseous objects in the Cosmos. Thus, the cold, dark spaces between the stars radiate most intensely at the longer, invisible radio wavelengths, while a hot, million-degree gas emits most of its energy at short X-ray wavelengths that are also invisible.

1.9 INVISIBLE FIRES

There is more to the Sun than meets the eye! In addition to visible light, there are invisible gamma ray, X-ray, ultraviolet, infrared and radio waves. The whole solar spectrum extends from short gamma rays: that are comparable to the size of an atom's nucleus, to long radio waves that are as broad as a mountain; and the Sun is so bright that it can be examined with precision in every spectral region. Observations at these invisible wavelengths have indeed broadened and sharpened our vision of the Sun.

However, our atmosphere effectively blocks most forms of invisible radiation including ultraviolet and X-ray radiation. Radio waves are the only kind of invisible radiation that is not absorbed in the Earth's atmosphere, so radio astronomy provided the first new window on the Sun.

FIG. 1.11 Very Large Array Each of the 27 radio telescopes of the Very Large Array, abbreviated VLA, measures 25 meters in diameter, or about the size of house, and weighs 235 tons (2.35×10^5 kilograms). These telescopes are placed along the arms of a Y-shaped array on a desert near Socorro, New Mexico, and interconnected electronically to provide a total of 351 pairs of telescopes. The telescopes can be rolled along tracks to change their configuration and create a radio zoom lens. When the telescopes are pushed to the outer ends of each arm and their output combined in a computer, the VLA creates a radio telescope with a diameter as large as 34 kilometers and an angular resolution that can be smaller than 1 second of arc. (Courtesy of NRAO, AUI and NSF.)

Astronomers use conventional radio telescopes to observe the Sun (Fig. 1.11); but radio telescopes do not really look at the Sun, they listen to it. Such telescopes usually have a metallic, dish-shaped, or parabolic, reflector that focuses the radio waves at a receiver. The long, straight antenna on your automobile or home radio similarly intercepts radio signals. Moreover, the Sun is the brightest, noisiest radio object in the sky, and because the atmosphere does not distort radio signals we can observe the radio Sun on a cloudy day, just as your home radio works even when it rains or snows outside.

To look at the Sun through windows other than the radio or visible ones, we must loft telescopes above the atmosphere. This was done first by using balloons and sounding rockets, and then with satellites that orbit the Earth above the atmosphere. Satellite-borne telescopes now view the Sun at ultraviolet and X-ray wavelengths, above the Earth's absorbing atmosphere at places where night can be brief or non-existent.

Thus, astronomers now have new ways to extract previously unobtainable information about the Sun. They are aided by new telescopes and sophisticated computers that gather in an increasing wealth of unsuspected information. Computerized telescopes now operate, from the ground and in orbit, in each of the invisible domains of the electromagnetic spectrum, creating images that provide new insight to the Sun.

Much of this book describes the invisible Sun, an unseen world of perpetual change and cosmic violence that lies outside the visible solar disk. And as the title *Sun, Earth and Sky* suggests, our book also describes the Sun's interaction with planet Earth, mainly through invisible radiation and tiny, energetic particles that cannot be seen. It involves a global, space-age perspective that looks up at the Sun and down at the Earth, at both visible and invisible wavelengths, or directly samples the space outside Earth with orbiting satellites.

But before we begin our journey through these largely invisible realms, there is an equally fascinating world that lies hidden below everything we can see on the Sun; clever techniques are required to perceive this unseen interior of the Sun.