SUN, EARTH AND SKY

SECOND EDITION

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Kenneth R. Lang

Second Edition

Springer

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Cover illustration: An extreme ultraviolet image of the Sun with a huge, handle-shaped prominence (*top right*). It was taken on 14 September 1999 at a wavelength of 30.4 nanometers with the Extreme-ultraviolet Imaging Telescope, abbreviated EIT, aboard the *SOlar and Heliospheric Observatory,* abbreviated *SOHO.* Prominences are huge clouds of relatively cool dense plasma suspended in the Sun's hot, thin corona. At times, they can erupt, escaping the Sun's atmosphere. Emission in this spectral line shows the upper chromosphere at a temperature of about 60,000 K, or 60,000 degrees kelvin. Every feature in the image traces magnetic field structure. The hottest areas appear almost white, while the darker red areas indicate cooler temperatures. (Courtesy of the *SOHO* EIT consortium. *SOHO* is a project of international collaboration between ESA and NASA.)

Title page illustration: A large, soft X-ray cusp structure (*lower right*) is detected after a coronal mass ejection on 25 January 1992. The cusp, seen edge-on at the top of the arch, is the place where the oppositely directed magnetic fields, threading the two legs of the arch, are stretched out and brought together. Several similar images have been taken with the Soft X-ray Telescope (SXT) aboard *Yohkoh,* showing that magnetic reconnection is a common method of energizing solar explosions. (Courtesy of Loren W. Acton, NASA, ISAS, the Lockheed-Martin Solar and Astrophysics Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo.)

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Dedicated to Julia Sarah Lang

Here comes the Sun
Here comes the Sun and I say
It's alright
Little darling, it's been a long, cold, lonely winter.
Little darling it feels like years since it's been here.
Here comes the Sun. Here comes the Sun and I say
It's alright.
Little darling, the smiles returning to their faces.
. . .
Sun, Sun, Sun, Here it comes.

George Harrison

Preface to the Second Edition

The ***Second Edition*** of the popular ***Sun, Earth and Sky*** has been updated by providing comprehensive accounts of the most recent discoveries made by five modern solar spacecraft since the publication of the ***First Edition*** a decade ago. The *SOlar and Heliospheric Observatory,* abbreviated *SOHO,* launched on 2 December 1995, has extended our gaze from the visible solar disk to within the hidden solar interior and out in all directions through the Sun's tenuous million-degree atmosphere and solar winds. *SOHO's* recent insights have been complemented and extended by other solar spacecraft, including *Ulysses,* which sampled the solar wind during two complete circuits around the Sun, and *Yohkoh,* which completed a decade of observations of solar X-rays. The *Transition Region And Coronal Explorer,* abbreviated *TRACE,* which was launched on 2 April 1998, has provided years of high-resolution, extreme-ultraviolet observations related to the heating of the million-degree outer atmosphere, and its ubiquitous magnetic loops, as well as energetic explosions on the Sun known as solar flares. The *Ramaty High Energy Solar Spectroscopic Imager,* or *RHESSI* for short, launched on 5 February 2002, has revealed new aspects of solar flares, observing them at gamma-ray wavelengths.

Whenever possible we have used new images of the Sun, from the *RHESSI, SOHO,* and *TRACE* spacecraft, many of them never published in book form before. When relevant, line drawings have also been updated. And we have retained works of art that begin each chapter, providing another fascinating perspective of our life-sustaining Sun.

During the past decade, solar astronomers have provided answers to several outstanding mysteries of the Sun, and given us new clues to numerous open questions that remain.

Years of *SOHO* observations of solar oscillations have been combined to look deep inside the Sun, determining its internal rotation to the greatest possible depths and establishing the location of the solar dynamo that amplifies and maintains the Sun's magnetic fields. The detailed mechanisms for creating solar magnetism are nevertheless still lacking.

In the past decade, breakthrough observations with the massive subterranean neutrino detector, the Sudbury Neutrino Observatory, have solved the Solar Neutrino Problem, revealing new physics of the ghostly neutrino, which has a tiny mass and changes form as it moves from the Sun to Earth.

Our ***Second Edition*** also presents several plausible mechanisms that might heat the corona to million-degree temperatures, hundreds of times hotter than the underlying visible solar disk. And it describes the location of energy release for solar flares within the low corona. The exact methods of continuously heating the corona and accelerating particles to enormous energies during solar flares are still open questions.

This ***Second Edition*** of ***Sun, Earth and Sky*** includes answers to the age-old questions of why the Sun shines, and how long it has been shining and will continue to shine, providing life-sustaining heat and light to Earth. And we also describe what the Sun is made of, and where its ingredients came from.

The volume also contains extended discussions of Space Weather, whose importance has grown during the past decade. Our technological society has become increasingly vulnerable to storms from the Sun that can kill unprotected astronauts, disrupt global radio signals, and disable satellites used for communication, navigation, and military reconnaissance and surveillance. We therefore describe methods of forecasting Space Weather, as well as taking evasive action for their threat on the ground or in space.

Recent signs indicate that global warming by human emissions of heat-trapping gases is increasing. The evidence comes from direct measurements of rising surface air temperatures and subsurface ocean temperatures, and from phenomena such as retreating glaciers, increases in average global sea levels, and changes to many physical and biological systems. The book describes these warning signs, the likely future consequences of global warming, and efforts to do something about it, including the *Kyoto Protocol* that went into effect in 2005 without the participation of the United States.

An annotated list of Further Reading is included, for books published between 1995 and 2005, and a Directory of Web Sites includes links to obtain information about total eclipses of the Sun, solar observatories and spacecraft, and space weather. An extensive Glossary completes this ***Second Edition*** of ***Sun, Earth and Sky***. Its preparation was made possible through funding by NASA Grant NAG5–11605, from NASA's Earth-Sun System Program, and NNG05GB00G with NASA's Applied Information Systems Research Program.

Kenneth R. Lang
Tufts University *and* Anguilla, B.W.I.
January 1st, 2006.

Preface to the First Edition

This book was written for my daughter, Julia; her love and comfort have helped sustain me. It is a pleasure to watch Julia noticing details of everything around her. Children and other curious people perceive worlds that are invisible to most of us.

Here we describe some of these natural unseen worlds, from the hidden heart of the Sun to our transparent air. They have been discovered and explored through the space-age extension of our senses.

A mere half-century ago astronomers were able to view the Cosmos only in visible light. Modern technology has now widened the range of our perception to include the invisible realms of subatomic particles, magnetic fields, radio waves, ultraviolet radiation and X-rays. They are broadening and sharpening our vision of the Sun, and providing a more complete description of the Earth's environment. Thus, a marvelous new Cosmos is now unfolding and opening up, as new instruments give us the eyes to see the invisible and hands to touch what cannot be felt.

Giant radio telescopes now tune in and listen to the Sun, even on a rainy day. Satellite-borne telescopes, such as the one aboard the *Yohkoh,* or "sunbeam", satellite, view our daytime star above the absorbing atmosphere, obtaining detailed X-ray images of an unseen Sun. Space probes also directly measure the invisible subatomic particles and magnetic fields in space; for instance, the *Ulysses* spacecraft has sampled the region above the Sun's poles for the first time, and the venerable *Voyager 1* and *2* space probes may have found the hidden edge of the Solar System.

My colleagues have been very generous in providing their favorite pictures taken from ground or space. Numerous diagrams are included, each chosen for the new insight it offers. Every chapter begins with a work of modern art, illustrating how artists depict the mystical and supernatural aspects of the Sun or the subtle variations in illumination caused by changing sunlight. All of these images provide new perspectives on the Sun that warms our soul, and lights and heats our days, and on our marvelous planet Earth that is teeming with an abundance of life.

This book describes a captivating voyage of discovery, recording more than a century of extraordinary accomplishments. Our voyage begins deep inside the Sun where nuclear reactions occur. Here particles of anti-matter, produced during nuclear fusion, collide with their material counterparts, annihilating each other and disappearing in a puff of pure radiative energy.

Neutrinos are also created in the solar core; they pass effortlessly through both the Sun and Earth. Billions of the ghostly neutrinos are passing right through you every second. Massive subterranean neutrino detectors enable us to peer inside the Sun's energy-generating core, but the neutrino count always comes up short. Either the Sun does not shine the way we think it ought to, or our basic understanding of neutrinos is incomplete. Recent investigations suggest that the neutrinos have an identity crisis, transforming into a currently undetectable form.

Today we can peel back the outer layers of the Sun, and glimpse inside by observing its widespread throbbing motions. Visible oscillations caused by sounds trapped within the Sun can be deciphered to reveal its internal constitution. This procedure, called helioseismology, has been used to establish the Sun's internal rotation rate.

We then consider the Sun as a magnetic star. Its visible surface is pitted with dark, cool regions, called sunspots, where intense magnetism partially chokes off the outward flow of heat and energy. The sunspots tend to gather together in bipolar groups linked by magnetic loops that shape, mold and constrain the outer atmosphere of the Sun. The number of sunspots changes from a maximum to a minimum and back to a maximum every 11 years or so; most forms of solar activity vary in step with this magnetic sunspot cycle.

As our voyage continues, we discover that the sharp visible edge of the Sun is an illusion; a tenuous, hot, million-degree gas, called the corona, envelops it. This unseen world, detected at X-ray or radio wavelengths, is never still. Such observations show that the apparently serene Sun is continuously changing. It seethes and writhes in tune with the Sun's magnetism, creating an ever-changing invisible realm with no permanent features.

The *Yohkoh* X-ray telescope has shown that bright, thin magnetized structures, called coronal loops, are in a constant state of agitation, always varying in brightness and structure on all detectable spatial and temporal scales. Dark X-ray regions, called coronal holes, also change in shape and form, like everything else on the restless Sun. A high-speed solar wind squirts out of the holes and rushes past the planets, continuously blowing the Sun away and sweeping interstellar matter aside to form the heliosphere. The heating of the million-degree corona, which expands out to form this solar gale, is one of the great-unsolved mysteries of the Sun.

This book next considers violent solar phenomena that are detected at invisible wavelengths and are synchronized with the sunspot cycle of magnetic activity. In minutes, powerful eruptions, called solar flares, release magnetic energy equivalent to billions of nuclear explosions and raise the temperature of Earth-sized regions to about ten million degrees. Magnetic bubbles, called coronal mass ejections, expand as they propagate outward from the Sun to rapidly rival it in size; their associated shocks accelerate and propel vast quantities of high-speed particles ahead of them.

Our account then turns toward our home planet, Earth, where the Sun's light and heat permit life to flourish. Robot spacecraft have shown that the space outside our atmosphere is not empty! It is swarming with hot, invisible pieces of the Sun.

The Earth's magnetic field shields us from the eternal solar gale, but the gusty, variable wind buffets our magnetic domain and sometimes penetrates within it. Charged particles that have infiltrated the Earth's magnetic defense can be stored in nearby reservoirs such as the Van Allen radiation belts. Spacecraft have recently released chemicals that can illuminate the space near Earth. Other satellites have found a new radiation belt that contains the ashes of stars other than the Sun.

This voyage continues with a description of the multi-colored auroras, or the northern and southern lights. Solar electrons that apparently enter through the Earth's back door, in the magnetotail, are energized locally within our magnetic realm and are guided into the polar atmosphere where they light it up like a cosmic neon sign.

Unpredictable impulsive eruptions on the Sun produce outbursts of charged particles and energetic radiation that can touch our lives. Intense radiation from a powerful solar flare travels to the Earth in just eight minutes, altering its outer atmosphere, disrupting long-distance radio communications, and affecting satellite orbits. Very energetic particles arrive at the Earth within an hour or less; they can endanger unprotected astronauts or destroy satellite electronics. Solar mass ejections can travel to our planet in one to four days, resulting in strong geomagnetic storms with accompanying auroras and electrical power blackouts. All of these effects, which are tuned to the rhythm of the Sun's 11-year magnetic activity cycle, are of such vital importance that national centers employ space weather forecasters and continuously monitor the Sun from ground and space to warn of threatening solar activity.

The Earth is wrapped in a thin membrane of air that ventilates, protects and incubates us. It acts as a one-way filter, allowing sunlight through to warm the surface but preventing the escape of some of the heat into outer space. Without this "natural" greenhouse effect, the oceans would freeze and life as we know it would not exist. Long ago, when the Sun was faint, an enhanced greenhouse effect probably kept the young Earth warm enough to sustain life. Then, as the Sun became more luminous, the terrestrial greenhouse must have been turned down, perhaps by life itself.

The book next shows how the Sun's steady warmth and brightness are illusory; no portion of the spectrum of the Sun's radiative output is invariant. Recent spacecraft measurements have shown that the Sun's total radiation fades and brightens in step with changing activity levels. It doesn't change by much, only by about 0.1 percent over the 11-year sunspot cycle, but the Sun's invisible ultraviolet and X-ray radiation are up to one hundred times more variable than the visible output. Fluctuations in the Sun's visible and invisible radiation can potentially alter global surface temperatures and influence terrestrial climate and weather, alter the planet's ozone layer, and heat and expand the Earth's upper atmosphere.

To completely assess environmental damage by humans to date, and to fully understand how the environment may respond to further human activity, requires an understanding of solar influences on our planet. We must look beyond and outside the Earth, to the inconstant Sun as an agent of terrestrial change. It can both lessen and compound ozone depletion or global warming by amounts that are now comparable to those produced by atmospheric pollutants.

This book therefore next focuses attention on the Earth's protective ozone layer, that is both modulated from above by the Sun's variable ultraviolet output and threatened from below by man-made chemicals. The ozone layer protects us from the Sun's lethal ultraviolet rays, and progress has been made in outlawing the ozone-destroying chemicals. Our ability to reliably determine the future recovery of the ozone layer will depend on adequate knowledge of how it is damaged or restored by the Sun.

Our voyage then continues with a discussion of the Earth's varying temperature. Large natural fluctuations in the record of global temperature changes mask our ability to clearly detect warming caused by human activity, and numerous complexities limit the certainty of computer models used to forecast future global warming. Strong correlations suggest that the 11-year solar activity cycle may be linked to both the Earth's surface temperature and terrestrial weather.

The "unnatural" greenhouse warming might eventually break through the temperature record, if we keep on dumping waste gases into the air at the present rate. The probable consequences of overheating the Earth as the result of human activity are therefore next examined. They suggest that we should curb the build-up of heat-trapping gases despite the great uncertainties about their current effects.

Yet, it is the Sun that energizes our climate and weather. During the past million years, the climate has been dominated by the recurrent, periodic ice ages, which are mainly explained by changes in the amount and distribution of sunlight on the Earth. Variations in the Earth's orbit and axial tilt slowly alter the distances and angles at which sunlight strikes the Earth, thereby controlling the ponderous ebb and flow of the great continental glaciers.

Smaller, more frequent climate fluctuations are superimposed on the grand swings of the glacial/interglacial cycles; these minor ice ages may result from variations in the activity of the Sun itself. For instance, during the latter half of the seventeenth century the sunspot cycle effectively disappeared; this long period of solar inactivity coincided with unusually cold spells in the Earth's northern hemisphere. Observations of Sun-like variable stars indicate that small, persistent variations in the solar energy output could produce extended periods of global cooling or warming. So, a prudent society will benefit by keeping a close watch on the Sun, the ultimate source of all light and heat on the Earth.

I am grateful to numerous experts and friends who have read individual chapters and commented on their accuracy and completeness. They have greatly improved the manuscript, while also providing encouragement. They include Loren Acton, John Bahcall, Dave Bohlin, Ron Bracewell, Raymond Bradley, Ed Cliver, Nancy Crooker, Brian Dennis, Peter Foukal, Mona Hagyard, David Hathaway, Gary Heckman, Mark Hodor, Bob Howard, Jim Kennedy, Jeff Kuhn, Judith Lean, Bill Livingston, John Mariska, Bill Moomaw, Gene Parker, Art Poland, Peter Sturrock, Einar Tandberg-Hanssen, Jean-Claude Vial, Bill Wagner and Wesley Warren. None of them is responsible for any remaining mistakes in the text!

Special thanks go to my entire family – my wife, Marcella, and my three children Julia, David and Marina.

Kenneth R. Lang
Medford, February 1995

Contents

Icarus

The French painter Henri Matisse (1869–1954) thought that happiness is derived from never being a prisoner of anything, including success or style, and he represented freedom from imprisonment in his 1947 book *Jazz* with this cut-out entitled *Icarus,* who seems to be pushing against the downward pull of gravity, trying to break away, soaring into a bright blue sky, and set the human spirit free. Icarus' red heart symbolizes love, which can make one soar, run and rejoice. Its liberating and all-consuming nature can make one see the world anew. (Courtesy of Succession Matisse, Paris.)

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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).

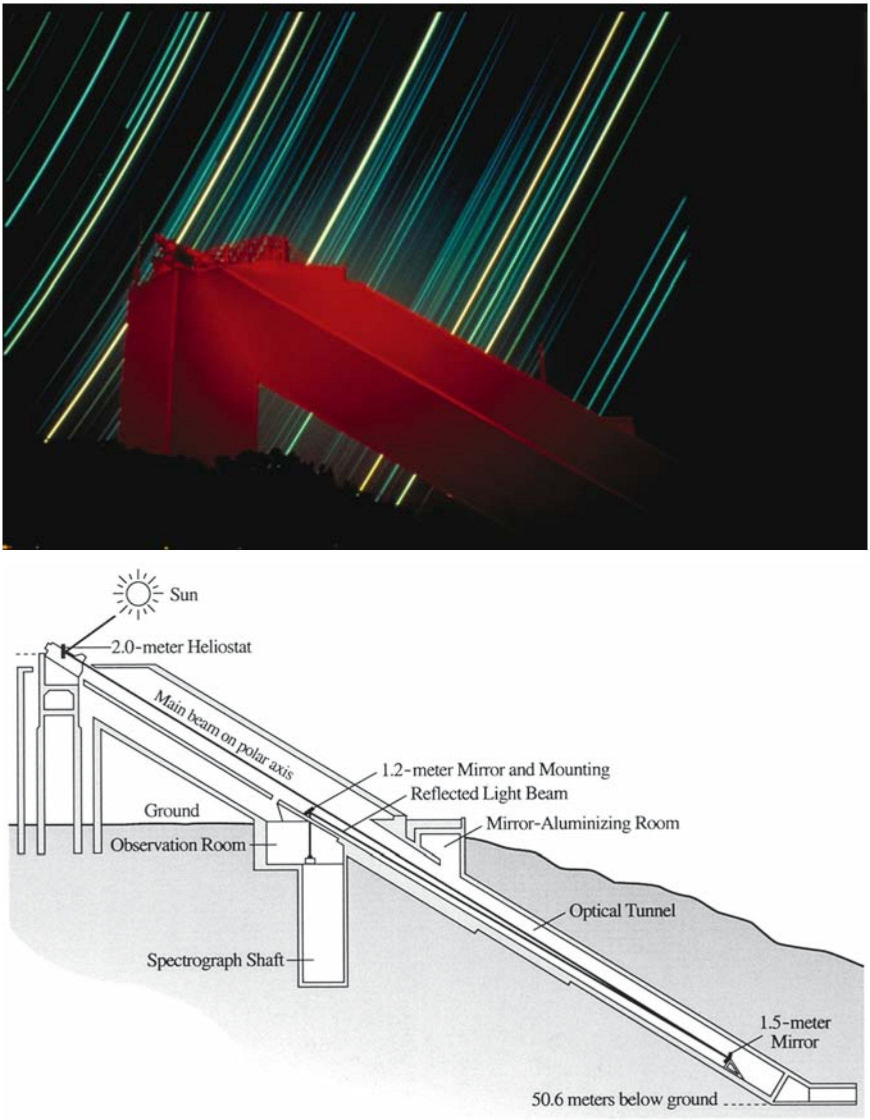

FIG. 1.5 **Eyes on the Sun** Scattered sunlight colors the McMath solar telescope a stunning red, while stars mark trails across the evening sky *(top)*. A moveable heliostat, perched atop this telescope, follows the Sun and directs its light downward through the long fixed shaft of the telescope (*bottom*). 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.

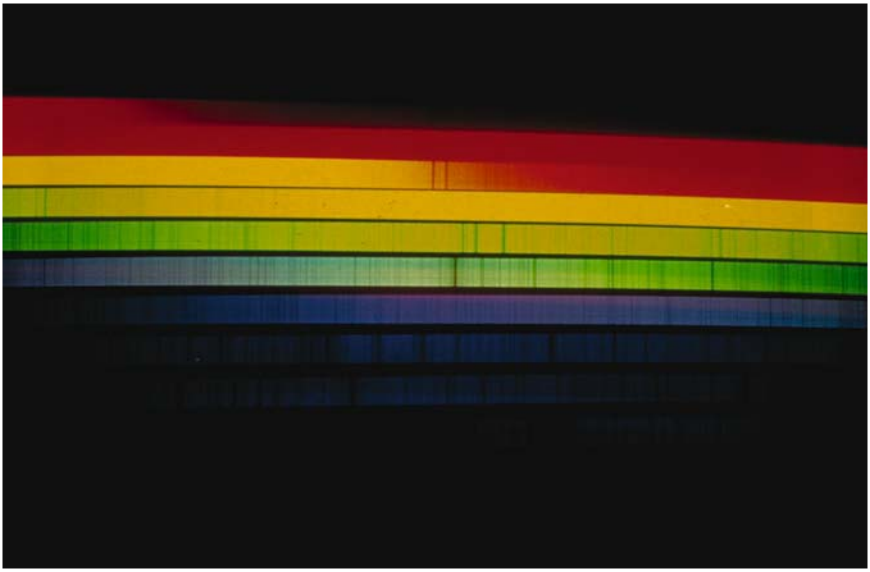

FIG. 1.6 Visible solar spectrum A spectrograph has spread out the visible portion of the Sun's radiation into its spectral components, displaying radiation intensity as a function of wavelength. When we pass from long wavelengths to shorter ones (*left* to *right, top* to *bottom*), the spectrum ranges 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

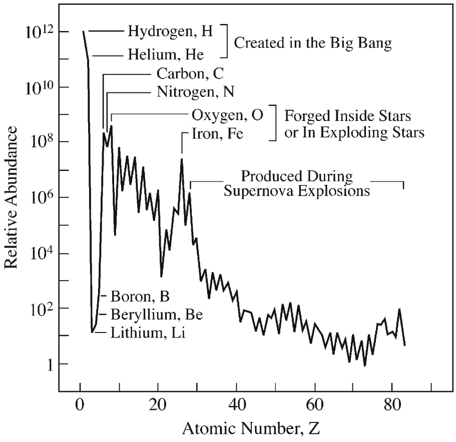

FIG. 1.7 **Abundance and origin of the elements in the Sun** The relative abundance of the elements in the solar photosphere, plotted as a function of their atomic number, Z. The abundance is specified on a logarithmic scale and normalized to a value a million, million, or 1.0×10^{12}, for hydrogen. 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