THE SUN

The Sun as a Star

The star we call the Sun is to us, of course, unique. Yet it is much like countless others in the sky that burn as bright and for as long. Some stars like Betelgeuse, a red supergiant star in Orion, are more than 500 times larger than ours, and others are a hundred times smaller, no larger than the Earth. Some are older, and many are younger. Among other stars in our Galaxy, our Sun is somewhat atypical in the sense that it is hotter and more massive than 80 to 90% of the rest. Still, were the Sun a person it would be seen by others around it in the sky as large, late middle-aged, reasonably well-behaved, and moderately bright.

The diameter of the Sun is about 100 times that of the Earth: large enough to hold about 100^3, or a million planets the size of ours, were they somehow stuffed inside it. While it doesn't seem that distant, the Sun is 93 million miles away, almost 400 times farther than our nearest neighbor, the Moon.

A Voyage to the Sun

Were we able to fly to the Sun in a commercial airliner at the speeds we are now accustomed to, the one-way trip would take more than twenty years. And after our arrival, should we choose to take a tour, a flight around the solar equator at the same speed would consume another eight months' time.

Once there we would find the star—though unbearably hot and blindingly bright—diffuse and ephemeral: gaseous throughout, like the atmosphere of the Earth, with no real boundary or surfaces. And nowhere to land. All we would see, up close, would be the luminous radiating surface, or photosphere: as bright and hot as a welder's torch, and fully as hazardous to look upon.

As is the case when viewed through a simple telescope from the Earth, the dimmer chromosphere, the graceful loops of solar prominences and the awesome corona, which loom high above the photosphere, would be wholly invisible to us in the awful glare of the searing white-hot, radiant surface. And this life-giving layer in the gaseous Sun—the fount from which all sunbeams flow—would appear not smooth and white but roiled and raging and turbulent: composed of an irregular mosaic of the close-packed tops of gargantuan convection cells, each carrying heat upward from deep within the Sun, like bubbles rising in a witch's cauldron.

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Scattered among them, from place to place, we would soon recognize—in the form of larger, slightly dimmer, gaping depressions—the fields of war where magnetic fields, emerging from below, hold back and reduce for a time, though not for long, the inexorable upward flow of convected heat. These are the well-known and long-counted sunspots—many larger than the Earth—whose numbers wax and wane in the course of an inexact cycle of about eleven years.

But nothing we see on the Sun, from near or far, is there to stay: like dancing flames in a fireplace, all that is visible to us is impalpable, ethereal and ever changing. The Sun is something of a paradox in this regard: the oldest, largest and heaviest elephant in the solar system, tipping the scales at more than 1015 trillion tons, and yet—when seen up close—displaying an almost unbearable lightness of being.

What is more, nothing that we see—not sunspots, not the bright surface nor all that lies above it—is as dense as the last vestiges of air that remain at the altitudes where satellites circle the Earth, hundreds of miles high, where the barometric pressure is like that of a vacuum. Truth be told, had we taken our imagined airplane voyage to the star, we could have kept on flying, on the same course that took us there, directly into and inside the Sun. And although the solar interior would get ever denser and hotter the deeper we go, we could fly halfway toward the very center of the star—for eighteen days and another quarter million miles—before reaching anything half as dense as the air we breathe at home.

We could never do this, of course, because of the crushing pressure that continues to increase the deeper we go inside the Sun; and in addition, the searing heat we would have felt long before our solar aircraft ever reached the photosphere.

Perpetual Combustion

What should amaze us is how the Sun can burn so brightly and continuously for so long a time. It is hard to imagine a fire so bright that we could feel its heat a mile away. And harder still the heat from a fire a hundred or a thousand miles away, no matter how large or hot it was.

Radiant heat from any source, large or small—the burner on a stove or the Sun in the sky—rapidly diminishes, by the square of the distance, as one moves away from it. Yet the heat emitted from the Sun—93 million miles away—is so intense that out of doors on a summer day we seek the shade.

The Sun has been shining in this way for about 4.6 billion years, about one third the age of the Universe itself, which is now thought to be 14 billion years. And the Earth—which is almost as old—has for at least the last 3.8 billion years been bathed in very nearly the same level of solar radiation that streams down on the planet today. The amount of solar light and heat that is intercepted by the Earth is about 5500 kilowatts per acre, or almost 2 x 10^{14} kilowatts over the entire daylit hemisphere.

Because our planet is so small a target at so great a distance, the portion of the Sun's emitted energy that we receive on Earth is a truly negligible fraction of what the profligate Sun pours out in all directions. The total radiative power released by the Sun, day in and day out, is about 4 x 10^{23} or 400,000,000,000,000,000,000,000 kilowatts. And like every other star in the sky, almost all of it is thoroughly wasted: thrown away and lost forever in the cold and dark of empty space.

THE EIGHT PLANETS AND PLUTO AS SEEN FROM THE SUN

PLANET	DIAMETER IN MILES	DISTANCE RELATIVE TO THAT OF THE EARTH	APPARENT SIZE RELATIVE TO THAT OF THE EARTH
Mercury	3000	.4	1
Venus	7500	.7	1.5
EARTH	**7900**	**1**	**1**
Mars	4200	1.5	0.4
Jupiter	88,000	5	2
Saturn	74,500	10	1
Uranus	31,600	19	0.2
Neptune	30,200	30	0.1
Pluto	1900	39	0.0001

Nor is what we or any other planet receives fully utilized. About 60% of the solar energy that arrives at the top of the atmosphere will make it to the surface of the Earth: the rest is absorbed and put to work in the air, or reflected and returned, unused, back into space. The amount that reaches the land or water at any place depends of course on its latitude and altitude, the time of year, and the clarity of the sky.

For the continental United States, the *average* daily radiation from the Sun that falls on one acre of land is equivalent to the energy released in burning 11 barrels of oil; or in one year, about 4000 barrels.

Were the Sun to bill us at the oil-equivalent rate for the solar energy we receive, the *average* annual *Sunshine Tax*, figured at $100 a barrel, would be $360,000

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for each acre we owned; and in some places in the sunny South and West—which receive almost twice as much sunlight as the continental average—well over half a million dollars per acre.

The Hidden Source of Solar Energy

The Sun is indeed huge, but no combustible fuel it might contain could stoke so hot a furnace so long a time; nor could a gradual gravitational shrinkage of the star, which until about a hundred years ago was thought to be the source of solar energy. It was then shown that given irrefutable evidence from geology of an Earth extremely old, the rate of contraction that was needed to supply the prodigious energy flowing outward from the Sun implied a grossly inflated ancient star. In fact, one with so great a girth that at the time when early forms of life were evolving on the Earth, our planet was tracing out its orbital path far inside the star it circled.

The real secret of the Sun's seemingly boundless energy—like that of all the other stars—is instead the nuclear processes that are triggered by the staggering pressures and temperatures deep within its central core: the fusion of single atoms of hydrogen into helium, with the release of some of the energy in each contributing atom in the form of heat. Because the Sun is made almost entirely of hydrogen, which is used up only slowly, this simplest of nuclear processes should continue to provide the Earth with adequate radiative energy for at least another five billion years. At about that time—for those who worry about such things—it is thought that the Sun will have used up its store of hydrogen fuel, and will expand about 100 times in diameter to join the ranks of the so-called red giant stars, like Arcturus and Capella.

Delayed Delivery

The heat created in the nuclear furnace, deep within the core of the Sun, works its way gradually outward to stoke the glowing surface of the star, almost half a million miles above the core. The path to freedom is at first exceedingly slow and tortuous, for the energy released in nuclear fusion is transmitted outward by individual collisions between single atoms of hydrogen and helium, in a medium that is incredibly compressed. To the Sun—that must ultimately expel every erg of newly released heat—the excruciating process of getting rid of it must seem as frustrating as a game of pool, played on a table infinitely long that is tightly packed from bumper to bumper with billiard balls.

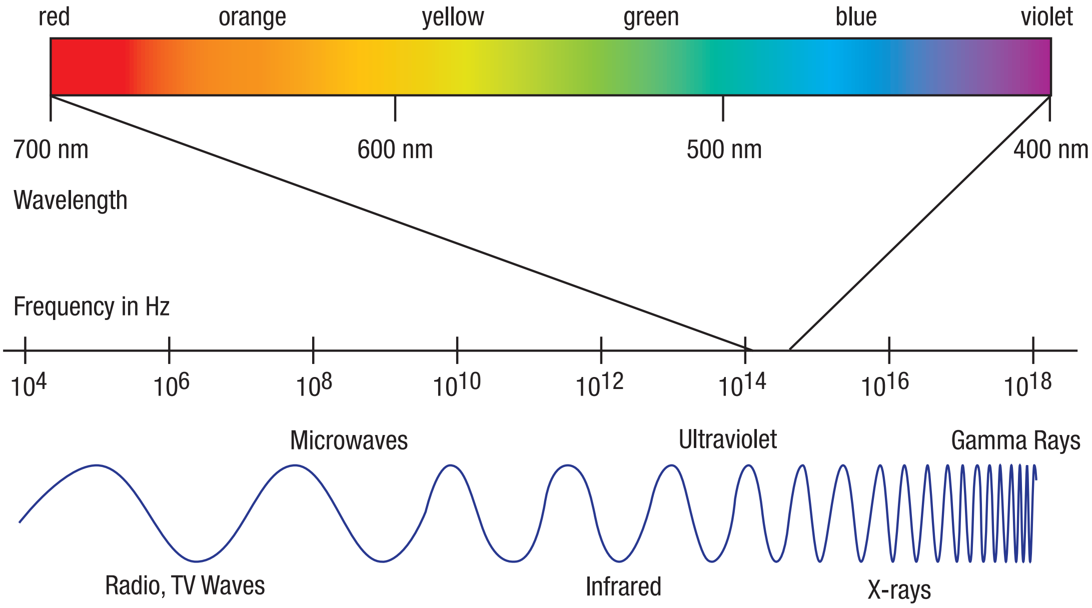
The density of matter within the Sun decreases steadily from the core to the surface of the star, and with fewer and fewer collisions farther and farther apart, the initially slow process of heat transfer gradually accelerates with distance from the center. Through the final third of the distance, the energy is no longer passed upward to the glowing surface by collisions between neighboring atoms, but carried up in bulk, through the upward movement of heated matter in giant convective cells. But despite the added speed of this final dash to the finish line, the heat that has finally worked its way outward from the core of the Sun to the visible surface of the star will have spent, on average, about 100,000 years en route.

Once there—free at last—it escapes the Sun as radiant heat: to race onward and outward at the speed of light. In but eight minutes it will reach the orbit of the Earth. There in the warm sunshine of a summer's day, we feel the heat the Sun produced a tenth of a million years ago, when woolly mammoths shared a simpler world with Stone Age men and women.

Radiant Energy from the Sun

Although the Sun also continually showers the Earth with energetic atomic particles, all but about 0.00001% of the energy we receive from the star comes to us in the form of radiant energy spanning a wide range, or spectrum, of wavelengths. About 80% of it is given off in the form of light (the visible spectrum, containing all the familiar colors of the rainbow) and as heat (the infrared spectrum, which we feel but cannot see). Most of the rest comes in a broad span of the more energetic and potentially harmful ultraviolet spectrum, which is also invisible to our eyes. A small fraction—less than 1% of the total—arrives in the form of even more energetic, potentially damaging, and also invisible x-rays and gamma rays, and as harmless emissions in a wide spectrum of radio waves at the other end of the electromagnetic spectrum.

It comes as no surprise, given the source of light in which life evolved, that the spectral response of our own eyes is so similar to the spectral distribution of radiation from the Sun. This is not the case for stars that are significantly hotter or cooler than the Sun, whose peak emissions are shifted, respectively, toward the violet or the red. Thus we bear in our genes an identifier of the type of star with which we live.



The portion of radiation from the Sun or other source that can be seen by the human eye as visible light (upper bar) in the context of the full range of electromagnetic radiation. Electromagnetic radiation is specified in terms of frequency of oscillation in cycles per second, or hertz (Hz) or alternately, the corresponding distance between crests of adjoining waves (wavelength). Radio radiation, at the far left, includes the lowest frequencies and the longest wavelengths, which can be as long as thousands of miles. At the other end of the spectrum is gamma radiation, with wavelengths shorter than the dimensions of a single atom.

How Constant Is and Was the Sun?

We should expect the Sun's total output of radiant energy to be nearly constant, by virtue of the enormous mass and thermal inertia of the star. Fluctuations in energy production in the core, or elsewhere beneath the surface, should be leveled out in the lengthy and tortuous processes through which heat is passed, hand over hand, through the interior of the Sun.

More gradual changes over billions of years in the Sun's luminosity are not ruled out by this argument. And indeed, what we know of how stars like ours evolve with time makes it almost certain that two or three billion years ago—when the Earth was new and the Sun was young—the Sun was as much as a third dimmer than today. Thus, in the course of its long life, it has indeed changed, and by quite a bit.

We also know from geology and paleontology that much of the surface of the Earth has been covered with water, and with life, for billions of years without interruption. From that crude datum we can say that the Sun has never burned so bright as to cause the oceans to boil during this long period of time. Nor so feebly that all the oceans froze. But neither of these tells us very much regarding the actual range, through time, of solar inconstancy.

What most of us should like to know is how constant and reliable is the Sun today, and whether solar radiation has varied significantly in the past hundred or perhaps a thousand years, and how much it will likely change in the future.

Metered Sunshine

We can now record, from minute to minute, all the changes that occur in the total amount of sunshine that reaches the Earth. But only since 1978, when the first precision instruments capable of making these difficult measurements of total solar irradiance were put in orbit about the planet. Generations of astronomers before that had attempted to answer this oldest of questions about the Sun from the tops of mountains and other high elevation sites, but their efforts were always limited by uncertainties in the variable absorption of solar radiation in the Earth's atmosphere.

We can now monitor as well the course of change in different spectral components, such as the solar ultraviolet or solar infrared radiation. As suspected, all forms of radiant energy that the Sun emits fluctuate on all time scales. The greatest variability is found in the shortest wavelengths—in our receipt of solar x-rays and ultraviolet radiation—and in the longest solar radio waves. The least variability is found in the visible and near-infrared regions of solar radiation. These latter two are also the greatest contributors, by far, to the total amount the Sun emits. As a result, we should expect the total solar irradiance, as measured at the Earth, to vary only slightly.

Continuous measurements taken since 1978 show that in this period the total radiant energy received from the Sun at the top of our atmosphere has indeed changed very little. But "constant" it is not, for it varies from minute to minute, day to day, and year to year, largely in response to the changes we see on the visible, white-light surface of the star. Darker (and hence cooler) sunspots, competing with brighter and hotter areas found around them and around the perimeters of convection cells continually tweak the total energy emitted from the visible hemisphere of the Sun.

Due to these changes on the surface of the Sun, the heat and light delivered at the top of our atmosphere can vary from day to day through a range of about ± 0.3%, and in annual average, from year to year, by about 0.07%. Neither of these solar fluctuations is as large as the everyday fluctuations in the voltage that supplies the lighting in our homes and places of work.

The change of about 0.07%, peak-to-peak, in annual-averaged measurements of solar radiation is among the simplest and most predictable of solar variations, for it marches to the drum beat of the well-known 11-year sunspot cycle. The total radiation released by the Sun into space is—somewhat surprisingly—greatest in those years when there are more sunspots on its surface, at which time increased magnetic activity brightens other regions on its surface. It then decreases by about 0.07% in the six or seven years it takes for solar activity to decline to a minimum level, when fewer sunspots are found.

Though far smaller in magnitude than the effects of daily changes in cloud cover or the annual variation of the Earth's distance from the Sun, this periodic change of 0.07% in total solar irradiance is enough to alter the temperature of both the air and the surface oceans. And indeed, measurable changes of the predicted amount and expected phase (warmer in years of maximum solar activity) have now been found. The impacts of charged atomic particles from the Sun—which also follow the 11-year solar cycle—could leave similar solar marks on the global climate record. How much the outputs of the Sun vary over longer periods of time is today a pressing and as yet unanswered question.

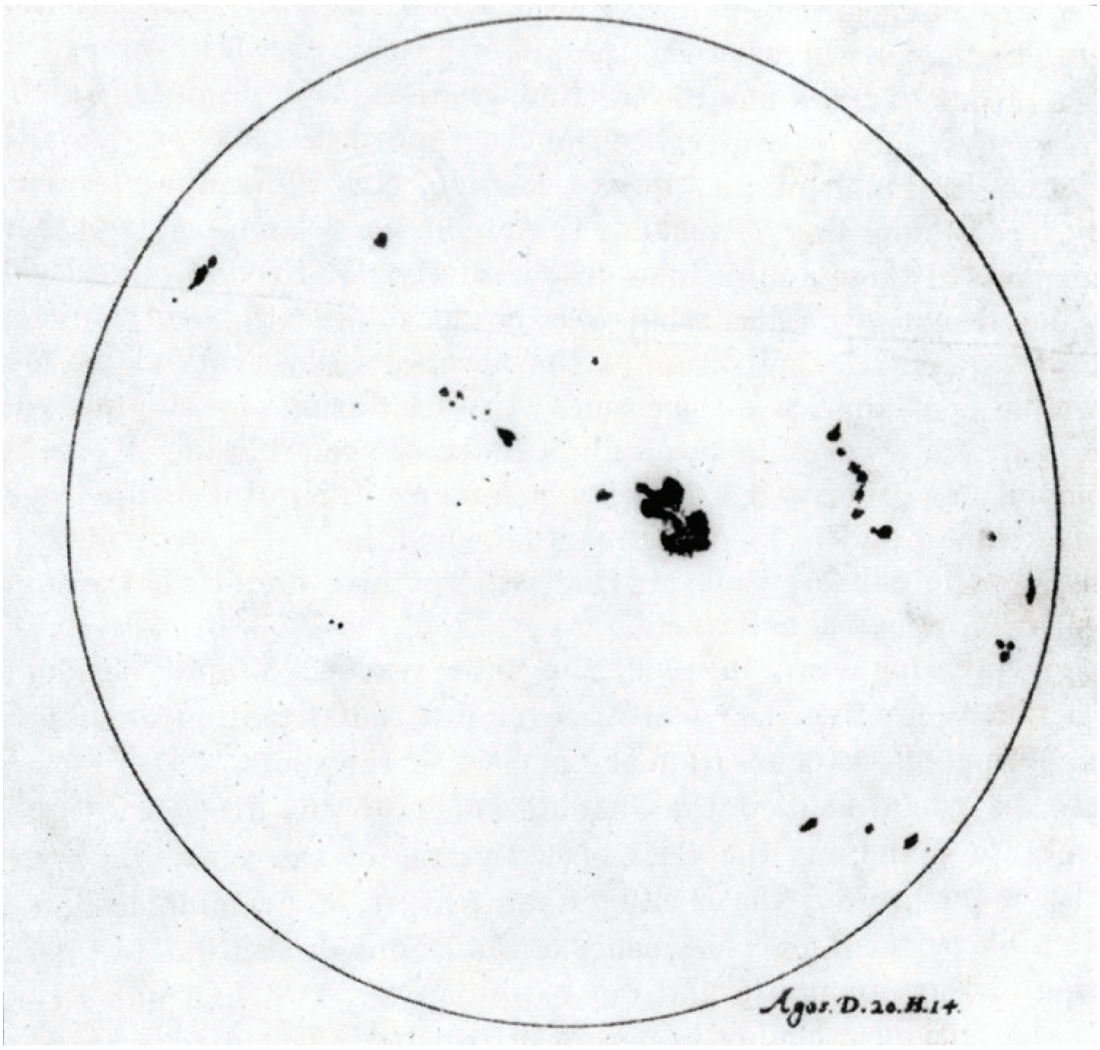
The First Who Saw the Face of the Sun

In Tuscany, in the summer of 1611, Galileo Galilei, then forty-seven, turned his small telescope on the Sun and projected its image on a white screen an appropriate distance beyond the eyepiece, where it was safe to view. At about the same time, three other men, quite on their own and far away, had begun as well to examine the bright disk of the Sun in the same way, like Galileo, with the aid of the newly-invented telescope: Thomas Harriot in England, Johann Goldsmid in Holland, and Christopher Scheiner in Rome. Though they would never meet, these four early explorers of the sky—three scientists and a Jesuit priest—were the first people to look so closely into the face of the star that lights the world.

None of them, including Galileo, claimed to have "invented" the telescope, which had been stumbled upon, purportedly by accident, in a spectacle-maker's shop in Holland a few years before. But it was Galileo—who knew the most about astronomy and optics and the art of reaching and convincing others—who applied the newfound tool most critically and effectively.

His early telescopes, like those of his three competitors, magnified what one could see with the eye alone by about a factor of thirty, and were made of rolled metal tubes not more than an inch or two in diameter and about a yard long. With these truly revolutionary devices Galileo had in 1609 and 1610, from his home in Florence, first looked at the Moon (to find valleys and mountains); at Jupiter (to discover four moons that circled that large and far away planet); at the Milky Way (to find it filled with stars so numerous as to be almost beyond belief); and at Mercury, Venus, Mars, and distant Saturn: which, with Jupiter, were at that time all the known planets in the sky.

What Galileo and the others found on the face of the Sun was a scattering of small dark spots of varied sizes, which were not fixed in place, but seemed to move from day to day across the solar disk. That there were imperfections of any kind on what was deemed to be the Sun's pure white surface may have come as a surprise to all of these first telescopic observers, for sunspots were not known in Europe or in most of the rest of the world at the time. In truth, Galileo and his three contemporaries were not the first to find them. Dark spots on the Sun, seen with the unaided eye, had been reported a long time before, in ancient Greece, and on at least one occasion in medieval Russia. And in China they had been more or less continuously observed, described and recorded since well before the time of Christ.

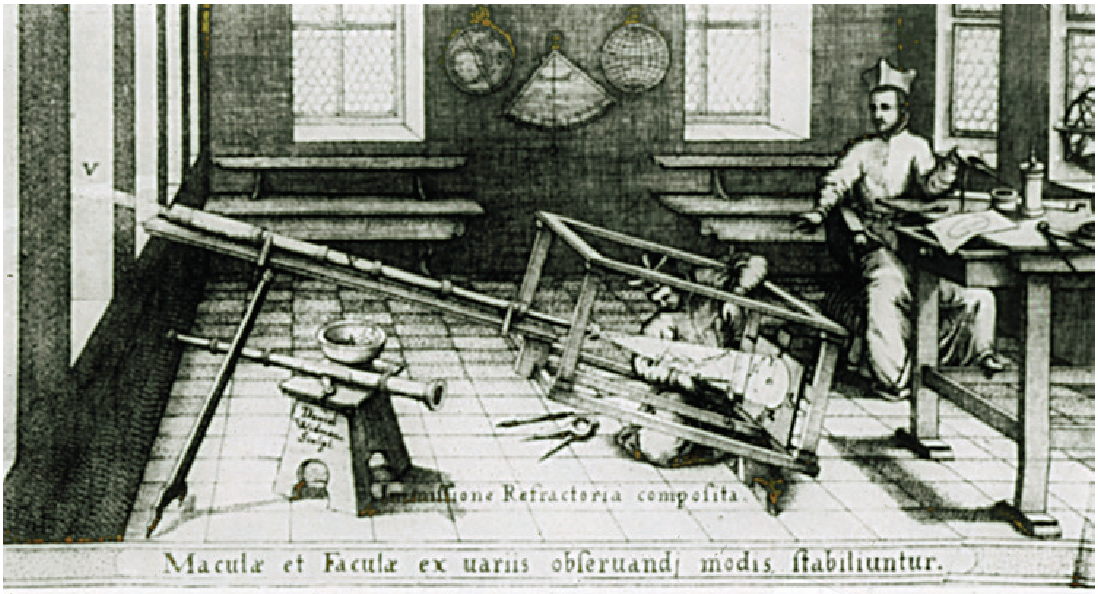


A drawing of the full disk of the spotted Sun made in Florence by Galileo using a small telescope at about 2 o'clock in the afternoon of August 20, 1610, looking much as it does today.

Sunspots that are sufficiently large can be seen without the help of a telescope, at those times or places when the blinding disk of the Sun is sufficiently dimmed. This is possible, for instance, when the Sun is seen through the smoke of a forest fire. One can also do it with the aid of a smoked glass filter that is sufficiently dark; by reflection in water that is smooth and very still; through thick clouds or haze; or at sunrise or sunset when the disk of the Sun is reddened by our atmosphere.

Since well before the time of Christ, sunspots were watched for in one or more of these ways by court astrologers in China (and later in Korea and Japan) who read them in terms of portents, often dire. They also left behind a well-preserved record of their relative sizes and when they were seen, in authorized dynastic histories. But without the help of a telescope, these early Eastern watchers of the sky could not clearly resolve the dark spots which they saw come and go on the face of the Sun, beyond simple, intriguing descriptions such as "as large as a plum", or sometimes "a duck's egg".

Galileo was in a position to make this distinction, and soon did. He concluded that the dark spots were too irregularly shaped to be planets encircling the Sun—as church apologists, including Father Scheiner in Rome, had hastened to propose. They were instead dark features on the Sun's own surface: which was not at all a divinely perfect fire. He also deduced from the manner in which sunspots appeared to move across its face that the Sun rotated, in a period of about 26 to 27 days, and that the Sun's axis of rotation was tilted by a few degrees.



Father Christopher Scheiner and another cleric tracing the image of the spotted Sun early in the 17th century, by projecting the image of a long focus telescope on a sheet of paper. The etching is from Scheiner's massive book on sunspots, the *Rosa Ursina*, published in Latin in 1630.

These robust findings, he concluded, strongly supported the proposition put forward more than half a century earlier by the astronomer Nicholas Copernicus in Poland. Namely, that the Earth was *not* the center of the universe, fixed in space with the planets and the Sun and all the other stars rotating once each day around it, as had long been taught. Instead, it is the Earth that moves around the Sun, spinning on its own axis once each day, while tracing out a year-long course around a tilted, turning and imperfect Sun.

To church authorities—the Christian fundamentalists of his day—these then-controversial views were deemed heretical in that they appeared to contradict the literal interpretation of certain words in the Holy Bible. For this perceived transgression, Galileo—a devout Catholic—was brought to trial in Rome. There he was found guilty of heresy; made to publicly recant what he had said and written; forbidden to teach or publish; and held under house arrest for the remaining years of his life, until the day of his death in 1642.

The Long Watch

Because the photosphere is easily viewed and ever changing, this best known layer of the gaseous Sun has been kept under nearly continuous telescopic surveillance since Galileo's time: watched and monitored through the years by an unending succession of both amateur and professional astronomers. As a result, there exists today in the form of collected descriptions, drawings, and ultimately, photographs, a diary of our star that tells first-hand of changes on the face of the Sun through a span of nearly 400 years.

The white light Sun was regularly watched and carefully documented throughout the 17th and 18th centuries, fueled by the European re-discovery of sunspots in 1611; by Galileo's short book, published in 1613, announcing his findings; by Father Scheiner's massive shelf-bending tome, published in Latin in 1630, which with elegant illustrations, detailed his own daily observations of sunspots; and by the interest of nearly every astronomer of note in the course of those two centuries.

Since early in the 19th century there are observations on record of how the face of the Sun appeared on every day of every year. And in 1848 the long-kept watch was organized into an international effort. Not long after, daily photographs of the solar disk were added to the global patrol; although daily drawings of the spotted Sun—made much as Galileo and Scheiner had done—were still employed for certain purposes for another hundred years and more.

The reasons for keeping so continuous a watch on the Sun changed through the centuries. Initially it was intellectual curiosity and a search for answers: to identify the characteristics and behavior of the dark spots (in Latin, maculae) and the bright patches (called, in part to rhyme with this, faculae, or little torches) that were often seen in close proximity to them when they were observed near the edge of the solar disk. What causes these bright and dark marks on the face of the Sun? What do they tell of the health of the star, or of its inconstancy? In what ways might they affect the Earth?

With the announcement, in 1843, of a more or less regular variation in the number of spots seen on the Sun—rising and falling again in a period of about ten years (later eleven)—the interest in sunspots increased.

Not long after that time, observations of the photosphere made with the new-found spectroscope made it possible to determine the temperatures and pressures and eventually the strengths of the magnetic fields in sunspots and other features of the photosphere. It was these that at last unlocked the secrets of the changing face of the Sun.

Sunspots were *darker* because they were almost 30% cooler than the 10,000° F temperature of the surrounding photosphere. They were cooler because they defined those places on the white-hot surface of the star where strong magnetic fields, emerging from below the visible surface, inhibited the upward flow of heat from the interior of the Sun. Faculae were *brighter* because they were denser and hotter than the surrounding photosphere, and they too were related to the surface magnetic field.

In short, the Sun—though indeed dependable and in the long term, quite constant—was found to be a moody magnetic star on which internally-generated magnetic fields affect the inexorable upward flow of heat from deep within it. Moreover the appearance and demeanor of its radiating surface are entirely driven by the contortions and interactions of immensely powerful magnetic fields: what Oliver Wendell Holmes called *"the maelstroms of the photosphere"* in a prescient poem composed in 1882.

The Sun That We Can See

The *photo-* (or light) sphere is the name given the white-hot glowing layer of the gaseous Sun where almost all visible light and infrared heat originate. As such it is the deepest layer within the star that we can see directly with our eyes, and the deepest from which we can feel solar heat.

Nearly all the red, orange, yellow, green, blue and violet rays that we receive from the Sun—which when seen together, appear to us as white—come from the photosphere. As does the rainbow, which is but white light from the photosphere pulled apart in its passage through mist or rain and then fanned out to form a looming arc of the Sun's original palette of colors.

The same is true for the blue of the sky. It too is white sunlight from the Sun's bright photosphere, scattered over the dome of the day-lit sky by intervening molecules of air. This physical process preferentially scatters the blue and violet rays to lend color to the sky, while letting the rest of the sunlight slip through unseen. But like beauty itself, the blue we see and artists paint lies mostly in the eye of the beholder, for in truth, the daytime sky is predominantly violet. It is only our own retinas—which are less sensitive to violet light—that produce the beautiful blue.

The Photosphere

Today the photosphere is watched and monitored around the clock from solar telescopes in solar observatories around the world—and from the vantage point of space—with ever-better clarity and magnification.

One of the purposes for this close and continuing watch is to improve what we know of how photospheric features, including sunspots and faculae, alter the amount of heat and light that we receive each day from the Sun. Another is to refine our knowledge of the causes and sources of explosive solar flares, eruptive prominences, and coronal mass ejections, all of which originate in photospheric magnetic fields.

Behind each of these activities is our growing need to anticipate those solar changes that impact an ever more crowded and more technical world. Toward these ends, each improvement in our ability to look more clearly into the face of the Sun is a step in the right direction.

From his back yard in Florence and using his best telescope, employing the glass lenses he had ground himself, Galileo in 1611 was able to distinguish individual features on the Sun that were as small as about 2000 miles across—roughly the size of the Moon, or the continent of Australia—but nothing smaller than that. With early improvements in the telescope, Father Scheiner in the 1620s was able to resolve details within sunspots that were about two times smaller than what Galileo had been able to see, or about the size of Alaska. Fifty years ago, although telescopes were by that time much improved, what could be seen on the Sun from even the best observing sites was limited by turbulence and irregularities in our own atmosphere to features that were no smaller than the state of Texas, roughly 500 miles across.

Revolutionary advances in optics and technology have followed since then. Solar telescopes in space operate far above the blurring atmosphere and offer

The solar disk seen in white light from the SOHO spacecraft on October 28, 2003, showing (near the bottom in this figure) an unusually large and complex sunspot group which give birth to fast-moving coronal mass ejections and some of the largest solar x-ray flares ever recorded. The area encompassed by the large group of spots equaled that of at least 15 Earths, surpassing the size of Jupiter.

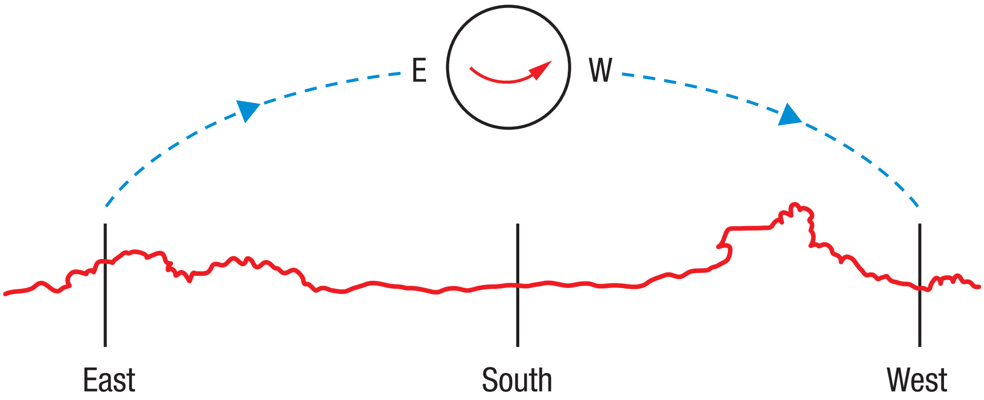
as well the ability to see the Sun in ultraviolet and x-ray wavelengths, not visible from the ground, as well as the ability to continuously observe the Sun's chromosphere and corona.

Ground-based solar telescopes, utilizing computer-controlled adaptive optics that automatically and continually compensate for irregularities in the air above them, are now able to distinguish features as small as 50 miles wide on the disk of the Sun. With the aid of this powerful new technology, the *Advanced Technology Solar Telescope (ATST)*—now under design at the National Solar Observatory—will allow tomorrow's solar observers to see and examine features as small as 12 miles in scale on the face of Sun, the size of downtown Denver, from 93 million miles away.

Sunspots

Far and away the best known features of the Sun are the black spots—ranging in size from too small to see with any telescope, to twice the size of the Earth—which are seen on its face in varying numbers on almost every day of every year. At no time are sunspots scattered over the whole Sun. They appear instead in restricted belts of solar latitude that gradually migrate from high solar latitudes toward the Sun's equator in the course of every 11-year sunspot cycle.

They also are most often clustered in separated groups, like flocks of birds. Individual spots are born small, grow in the course of their lifetime of days to weeks and sometimes months, and then fade from view. As Galileo noted, they all move systematically from the *left* or *eastern* edge of the Sun toward the *right* or *western* limb, carried along like autumn leaves on a brook, as the star turns slowly on its axis, completing each solar rotation in about 27 of our days.



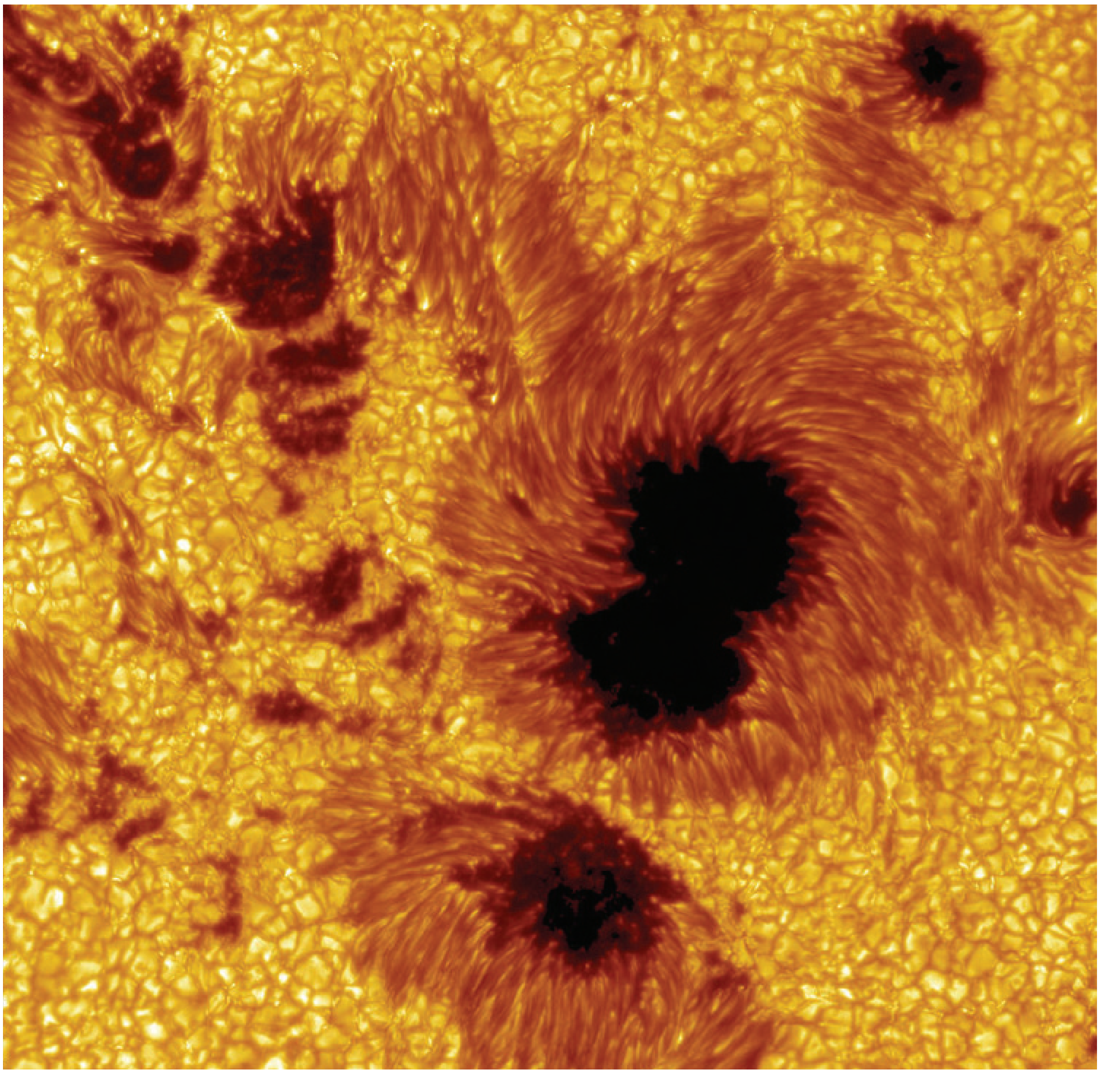
A schematic view of the horizon showing the daily east-to-west path of the Sun through the sky (as a dashed blue line), the direction of the Sun's rotation about its axis (as a red arrow) and the east and west limbs of the solar disk.

When seen through a small telescope of the sort that Galileo employed, most larger sunspots are found to consist of a darker and hence somewhat cooler central region—the umbra, meaning shadow, or shade—surrounded by a less dark fringe—the (partially shaded) penumbra. A closer examination of the penumbra reveals that it is made up of what look a lot like buttonhole stitches sewn around the perimeter of an umbral hole. In reality, these penumbral features are towering arches of heated solar gas that flow both into and out of the umbra of the sunspot, constrained by curved lines of magnetic force.

Any and all unsolved mysteries regarding sunspots—why they appear darker and take the varied shapes they do, where they come from, and what purpose they serve—were swept away forever when it was demonstrated, early in the last century, that sunspots are the sites of highly concentrated magnetic fields.

To summarize: sunspots are darker than the surrounding disk of the Sun because—though very hot by terrestrial standards—they are considerably cooler than the rest of the photosphere: about 7000° F instead of 10,000. They are cooler because they mark the places where lines of magnetic force, emerging from the churning interior of the star, are concentrated and clustered together, forming a kind of magnetic plug which at those places inhibits the upward flow of heat.

The penumbral arches delineate the boundary where the tightly packed vertical field lines in the umbra of a sunspot begin to spread and fan out, like the bloom on a lily.



A close-up, color-added view of the dark centers (umbrae) of sunspots; the less-dark, magnetically-formed penumbrae that generally encircle them; and the ubiquitous pattern of close-packed tops of the convective cells that characterize the entire photospheric surface of the Sun. This unusually clear image was made from the mountain-top La Palma observatory in the Canary Islands using the Swedish 1-meter high-resolution solar telescope, which employs automatically-adjusted optics to continually compensate for the blurring effects of turbulence in the Earth's atmosphere.

Bright Faculae

Brighter (and hence hotter) regions on the photosphere, called faculae, are another consequence of solar magnetic fields. A dermatologist would probably describe them as a rash of luminous blotches on the face of the Sun: larger and far more irregular in shape than sunspots; not as much brighter than the surrounding photosphere as sunspots are darker; but more extensive and spread over a larger area of the solar disk. They are also more ephemeral—living but a day or so—and ever changing. The largest are found in the close vicinity of sunspots, and like them the area of the Sun covered by faculae rises and falls in step with the 11-year sunspot cycle.

Due to their lower contrast, faculae are not easily seen with a simple telescope. This did not stop Galileo and Scheiner and the other early 17th century astronomers from finding them when these subtle brightenings were near the edge (or limb) of the solar disk, where they are far more apparent.

The faculae we see near the *left* or *eastern* edge of the Sun are carried by solar rotation toward the center of the solar disk where their apparent brightness—relative to the surrounding photosphere—rapidly fades, and they soon drop out of sight. A week or so later when the same facular areas approach the *right-hand*, *western* limb of the Sun they once again become more apparent. The reason why faculae can be seen at the edge but not the middle of the solar disk follows from their towering form and the background against which they are seen.

Faculae consist of vertical columns of magnetically-constrained gas that is hotter and hence brighter than the photospheric surroundings through which it flows. Because of this, faculae on the face of the Sun increase the total amount of heat and light that the Sun emits and we receive. The sunspots that labor beside them to hold back the outward flow of energy from within the star work in the opposite way, to diminish the total, in an ongoing Yin and Yang relationship that is probably as old as the Sun itself.

It never ends in a draw. In terms of day-to-day changes it is sunspots that hold the upper hand—and a heavy one—turning down the Sun's output of energy on any day by as much as several tenths of a percent. But in the longer run—when averaged over months to years—the faculae prevail, aided in part by other bright features of smaller scale more uniformly distributed on the solar surface that are even more difficult to see.

Both the number of spots and the prevalence of faculae rise and fall together in the course of the 11-year solar activity cycle. Since it is the bright features

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(and not the sunspots) that play the heavier hand, the Sun *brightens* and the heat and light we receive from the Sun systematically *increases* in the maximum years of the cycle. When there are fewer and fewer sunspots—in years of lower solar activity—the total radiation *decreases*. And although the change is less than 0.1 percent, it is enough to perturb our climate system, in part through persistence, by pushing in the same direction for months or years at a time.

Beneath the Shining Surface: The Bubble Machine

The photospheric background against which sunspots appear is itself highly structured: made up of a closely-packed honeycomb of brighter elements, each bounded by darker lanes. This intriguing, almost geometrical pattern, first described more than 200 years ago, covers the entire surface of the Sun, from pole to pole. Because the close-packed elements looked something like small pellets or grains, they were initially called granules, and the overall pattern the solar granulation.

Today we know that what we see as the granular, mottled photosphere is in fact the top surface of a deep convective layer that fills the entire outer third of the Sun's interior. Within this vast and ever churning region, some 150,000 miles deep, intensely hot gases heated by the Sun's nuclear furnace, far below, are made more buoyant and hence propelled upward—like bubbles in a heated kettle.

After continual jostling, interaction and exchange, some make it to the surface of the star. There in the crowded company of billions of other glowing granules they cool by giving up some of their energy in the form of radiant heat and light. Once cooled and therefore heavier, the hot gases within them sink down once more beneath the surface, to be reheated and fight their way to the top again.

The heated cells take their honeycomb form in a variety of shapes and sizes. The smallest we can yet discern are about 100 miles across; the average, twice the size of Texas; and the largest are about as big as the continental USA. But life at the top is a fleeting thing for any of them, large or small. Once there, they have but a few minutes in the limelight before up-and-coming others crowd into their place.

To help discharge their cargo of heat while at the surface of the Sun, each convective cell is internally stirred by patterns of flow that circulate hot gases upward in the center, outward toward the perimeter and then back down again at the sides. And while examples of churned mixing of this kind come readily to mind—as in a kitchen blender, or when stirring paint in a can—none of them works as fast or frenetically as these gigantic mixers on the Sun. Within each solar convective cell, the hot streaming gases are carried up, across, and down not like batter in a bowl but at the dizzying speed of a mile each second: faster than a speeding bullet.

Lifting the Veil: The Unseen Sun

Almost all that is known of the Earth's interior has been obtained indirectly, without ever seeing or sampling it. Particularly valuable is the application of seismology: the science by which one can probe the actual interior of the Earth by the way sound waves—initiated at the surface—are bent and reflected back again.

The study of the hidden interior of the Sun—of what lies beneath the photosphere—has made use of the same techniques, which in this application is called helioseismology: the study of the solar interior based on observable oscillations on its surface.

In terrestrial seismology, the disturbances that initiate sound waves include earthquakes and other natural tremors of opportunity as well as man-made disturbances that are set off for this purpose. In the case of the Sun the force that induces sonic waves is the ever-present piston-like up and down movement of material in the solar convection zone: like rambunctious children jumping up and down with all their might on the bed in a motel room.

In response to this incessant hammering, the entire photosphere is made to oscillate, in distinctive patterns of undulating waves that slosh slowly up and down, in a regular period of about five minutes. Some of this created energy is thought to heat the chromosphere and corona. Another part is directed back into the interior of the star, in the form of sound waves. These waves, as they pass through the nether world of the Sun, are refracted (or bent) by differences in the internal properties of the solar interior.

The bent paths of these solar sonic waves—like those that are employed to probe the inner Earth—ultimately take them back to the surface again, where they perturb the natural oscillation of the photosphere. It is these subtle differences in solar oscillation, measured and compared from point to point on the surface of the Sun, that are now used to reveal many of the secrets of the innermost Sun. For these purposes data are taken both from spacecraft and from a dedicated around-the-world network of automated ground-based stations.

The application of these techniques have confirmed the existence of a deep convection zone and plumbed its very bottom, 150,000 miles deep. They have

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helped illuminate what happens just beneath a sunspot, and the depth at which the bundled magnetic field lines that give it form and function begin to block the upward flow of heat within the Sun. And they have shed a bright new light on the origins of the Sun's varying internal magnetic field and the mechanisms within the Sun that control the birth, the places of birth and the regularly-varying numbers of sunspots and related features of solar magnetic activity that affect our own lives in down-to-Earth ways.

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The most fundamental finding from helioseismology, thus far, is probably the clear-cut information it provides on how the inner Sun rotates, and how the rate of rotation changes with depth and latitude.

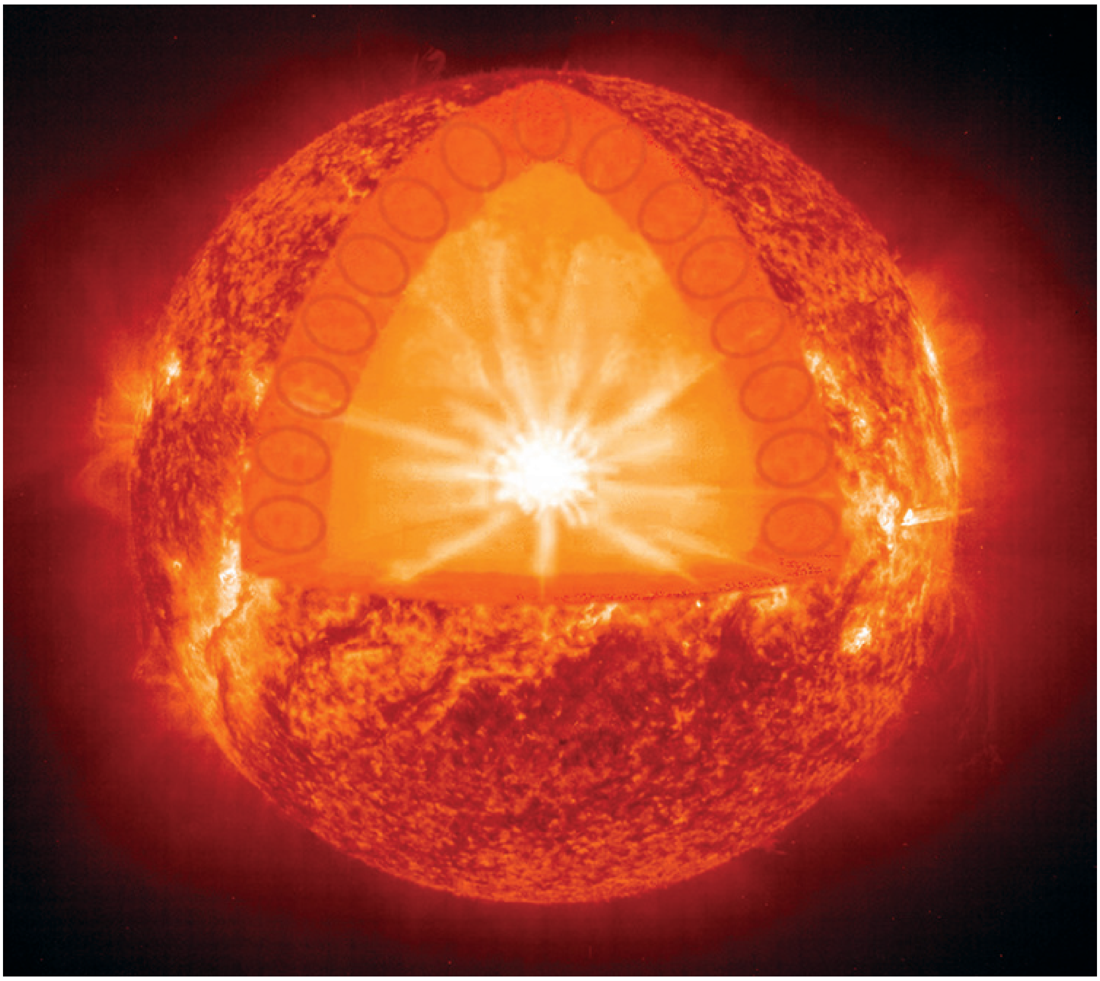
There is no reason to expect that the squishy, gaseous Sun should rotate like a spinning bowling ball—at the same rate everywhere, inside and out. Indeed, it has been known since Galileo's time that different latitudes on the surface of the Sun rotate at different speeds: completing a turn about five days faster at the equator than near the poles. Were the Earth to follow that solar recipe, the number of hours in a day (say, from noon to noon) would depend upon one's latitude: with each day in Anchorage or Saskatoon several hours longer than one spent on the beach at Waikiki.

Helioseismology has shown that the rate of rotation of the Sun also varies considerably with depth.

The Sun's convection zone—much like the visible surface of the star—rotates much faster at lower solar latitudes than it does nearer the poles. At the equator, it takes about 27 days for matter on the solar surface and in the convection zone beneath it to complete one full turn around the rotational axis of the Sun. Near the poles it takes almost half again as long to make the trip.

One consequence of this *internal* differential rotation is the distortion and twisting of sub-surface magnetic field lines. Magnetic lines of force within the Sun—which would otherwise run from pole to pole—are by differential rotation twisted into toroidal magnetic fields which lie in planes *perpendicular* the Sun's axis of rotation. This is one of the forces that bring internal magnetic fields to the surface to appear as sunspots and other manifestations of solar magnetic activity.

A second level at which differential rotation occurs is deep within the solar interior, at the depth where the bottom of the convection zone comes in contact with the hotter, deeper, denser, and dynamically different radiative zone that lies beneath it. At this level and below, solar material rotates as though it were indeed a solid inner sphere, in twenty-seven days—which is at high latitudes much faster than the convection zone that lies immediately above it. Nearer the equator it spins more *slowly* than the overlying convection zone.



The spherical Sun sectioned to show what lies beneath the chromospheric surface of the star. Within the bright central core (white) atomic hydrogen under extreme pressure and temperature fuses to create atoms of helium with an accompanying release of energy, which will ultimately escape from the photosphere. Surrounding the core is a vastly larger radiative zone (light orange) through which solar energy is passed outward from atom to atom by the process of radiation, like warmth from a room heater. When the energy passed in this way gets about two-thirds of the way to the surface of the Sun, it is transmitted further upward by the mechanical motion of circulating cells within the tumultuous convective zone (dark orange).

The result is continuous slippage and shear within a thin and troubled layer, called the tachocline, which separates these two interior shells.

It is also thought that the tachocline may be the layer where all solar magnetic fields are conceived, and as such, a fundamental piece of the basic mechanism—known as the solar dynamo—which drives eleven year and longer fluctuations in solar magnetic activity.

The Sun's Chromosphere and Corona

Although it looks that way when seen with the unaided eye or viewed through a simple telescope, the well-defined edge of the Sun is not its outer boundary. The familiar white photosphere is only the brightly shining core of a far larger star. Were the rest of the Sun (the chromosphere and corona) as bright it would appear more than ten times larger, and bounded by an ever-changing ragged and asymmetric shape.

The chromosphere is the relatively-thin, tenuous layer of the Sun that lies just above the photosphere. The name *chromo-* (or color) sphere comes from how this layer in the solar atmosphere appears during a total solar eclipse, when for but a few fleeting moments—just before and just after the moving Moon completely covers the full disk of the Sun—we see it edge on, in the intense red light of hydrogen.

Just above it is the more tenuous and far more extensive corona: literally the crown of the Sun, which is so completely different from the rest of the star that it seems like a ghostly other-world appendage. Contributing to this impression is the fact that this very real part of the Sun is so rarely seen. For most people, the only chance will come if they seek out or happen to be caught within the small, speeding shadow of the Moon (about 100 miles in diameter) during a total eclipse of the Sun, which last at most seven minutes. Because this happens at a given place, on average, only about once in 400 years, almost all who through time have lived on this planet never saw it, as most people today probably never will.

The chromosphere and corona, in part because they are more tenuous and diffuse, are so much less bright than the disk of the Sun that under normal conditions they are blocked from our view: much as the bright headlights of a close-approaching truck bar us from seeing the vehicle itself. And though a part of the Sun, they obey a quite different set of rules. Both the chromosphere and corona are non-uniform and highly structured, ever changing, often explosive, and shaped by magnetic forces into forms of awesome beauty.

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What is most surprising is that these outer reaches of the star are far hotter than the glowing photosphere that lies just below them, which flies in the face of all common experience and intuition. We expect the temperature in the vicinity of an internally-heated object, like the Sun or a cast-iron stove, to drop, not rise, as we move farther away from the source of its heat. But because of their make-up, these outer layers of the Sun are not bound by these laws of thermodynamics. Other, non-radiative sources of energy must be involved, although identifying them with certainty remains a challenge.

What heats the chromosphere and corona to such high temperatures? The auxiliary source of heat is most likely found in either the intense magnetic fields that thread these layers of the solar atmosphere, and/or the mechanical energy deposited at the base of the chromosphere from the relentless pounding of convection cells: the same source that imposes the undulating, five-minute patterns of oscillations in the photosphere. What is not fully understood is how mechanical energy deposited at the base of these cloud-like extensions of the Sun can heat the chromosphere and corona so far above it so efficiently.

From the core of the Sun outward the temperature falls steadily, mile after mile, through a distance of almost half a million miles: from about 29 million degrees Fahrenheit in the nuclear furnace to about 10,000°F at the radiating surface of the photosphere. For another few hundred miles above this visible boundary the temperature continues to coast downward until, about a quarter of the way through the thin overlying chromosphere, it has fallen to about 7000°.

There the temperature of the Sun abruptly reverses its long and leisurely fall. Within a very short distance above that point the temperature of the thin chromosphere jumps to about 20,000° F. Just above the chromosphere, in an even thinner transition zone that separates it from the corona, the temperature is ten times higher. And not far above that, in the new and different world of the solar corona, temperatures are measured in millions of degrees.

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The photosphere consists of both neutral and ionized atoms, as well as some molecules. With each increase in temperature—as one moves through the chromosphere and transition zone and into the corona—more of the atoms and molecules of any and all chemical elements are stripped of more and more of their electrons, producing more ions, carrying a positive charge, and free electrons with a negative one.

A collection of charged particles of this kind—common in the atmospheres of stars—which contains roughly equal numbers of electrons and positively charged ions, defines a fourth state of matter: not the solids, liquids or gases of our ordinary experience, but highly ionized atomic particles—or plasma. In this altered state it has sold its soul to magnetism, and is now subject to every whim of the lines of strong magnetic forces, rooted in the convection zone and photosphere, that twist and weave their way through the atmosphere of the

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Sun. In truth, above the photosphere all that is left of the star is controlled, in form and in function, by the Sun's magnetic field.

These magnetic lines of force confine and shape the solar plasma, molding it into the many forms that distinguish and decorate the outer atmosphere of the Sun. In the chromosphere, some magnetic field lines corral and organize the hot solar plasma into a pattern of close-packed super-sized granulation cells, 10,000 to 20,000 miles across and but 1000 miles deep, covering the entire Sun. The super-granulation cells that make up this overlying chromospheric network are bounded at their edges by hedgerows of tall, magnetically-formed spicules—or spikes—that carry hot confined plasma upward into the corona.

The largest and longest lived of the many magnetically-sculpted features in the chromosphere are the protuberances, now called solar prominences, that protrude in a variety of shapes high into the far hotter corona. They are for the most part formed of magnetic loops, the most spectacular of which appear above the edge of the Sun as towering arches—some active, some inactive or quiescent—that extend from about 30,000 to as much as 250,000 miles above the photosphere. In form and grandeur these large loops of cooler plasma look a lot like the Gateway Arch—were it painted a fiery red—that soars above St. Louis on the banks of the Mississippi: or croquet hoops of colossal scale, some tall enough for mighty Jupiter, the largest of the planets, to roll quite easily through them.

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Much of the lower corona is made up of magnetically-formed arches whose foot-points are rooted in the photosphere in regions of opposite magnetic polarity, most often in sunspots. In solar images made in the x-ray region of the spectrum, where radiation emitted by a million-degree plasma is best seen, the lower corona of the Sun is so heavily stitched with these magnetic loops that it looks a lot like one side of a Velcro fastener, awaiting the closure that will never come.

Coronal magnetic fields at low and middle latitudes shape the outward-flowing coronal plasma into tapered forms, called coronal streamers, which extend far into interplanetary space. Against the darkened sky of a total eclipse of the Sun, these graceful extensions of the outer solar atmosphere are made visible to us, looking very much like the petals of a white dahlia.

We see these and other features of the white and ghostly corona at times of a total solar eclipse not by their own weak emission of light but by the scattering or redirection of white light coming upward from the photosphere.

The white clouds we see in the sky are visible to us through a similar process: in this case the scattering of white sunlight by the microscopic water droplets which we would otherwise not see. The same scattering process illuminates nighttime fog in the bright headlights of an automobile, and droplets of mist that appear as a spherical glow around a street light.

In the corona the scattering particles are electrons which are particularly efficient scatterers. What we do not see in the corona are the protons and ions which are also present. Since these atomic particles are far heavier than electrons, they respond less readily to incident light from the photosphere. Like the Moon, or the water droplets that make up clouds, we see the scattering electrons only in the reflected light of the photosphere. Like clouds on Earth the outer corona is white because the photosphere is white. Were it purple or green the corona would be also.

Thus, during the few rare minutes of a total solar eclipse we are allowed to see—from 93 million miles away—the two ingredients of which the corona is made: electrons, which are so small that it would take 10^{30} of them to weigh 1/3 of an ounce; and the lines of force of the Sun's magnetic field, which like steel girders give shape and form to all coronal features.

Where coronal streamers appear and how fully they surround the central disk of the Sun is determined by the location and strengths of magnetic fields on the surface of the star. Because of this, the appearance of the corona, however it is observed, changes considerably from day to day and systematically from year to year with changing levels of solar activity.

The high latitude corona has its own distinctive appearance. There, the radial extension of the Sun's polar magnetic field arranges the coronal plasma into a crown of spreading polar plumes that encircle the poles, as though to guard them, like illumined palisades.

TEMPERATURES BENEATH, AT, AND ABOVE THE VISIBLE SURFACE OF THE SUN

LOCATION	TEMPERATURE IN DEGREES (F)
Nuclear fusion interior	29 million°
Photosphere	11,000°
Sunspot Umbra	7000°
Low Chromosphere	18,000°
Transition zone	180,000°
Inner Corona	2 million°
FOR COMPARISON: Industrial Blast Furnace	2000°
Oxy-acetylene Flame	6300°
Iron-welding Arc	11,000°

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How We See the Corona and Chromosphere

Two constraints keep us from seeing the Sun's outer atmosphere under ordinary viewing conditions. The first is the great difference between the brightness of the corona and underlying chromosphere and the adjacent photosphere, due to the immense difference in the density of matter in these outer and more ethereal layers. The chromosphere is ten thousand times dimmer than the photosphere when seen in the visible spectrum. The corona, in the innermost and brightest regions, is almost a million times dimmer than the brilliance of the adjacent solar disk.

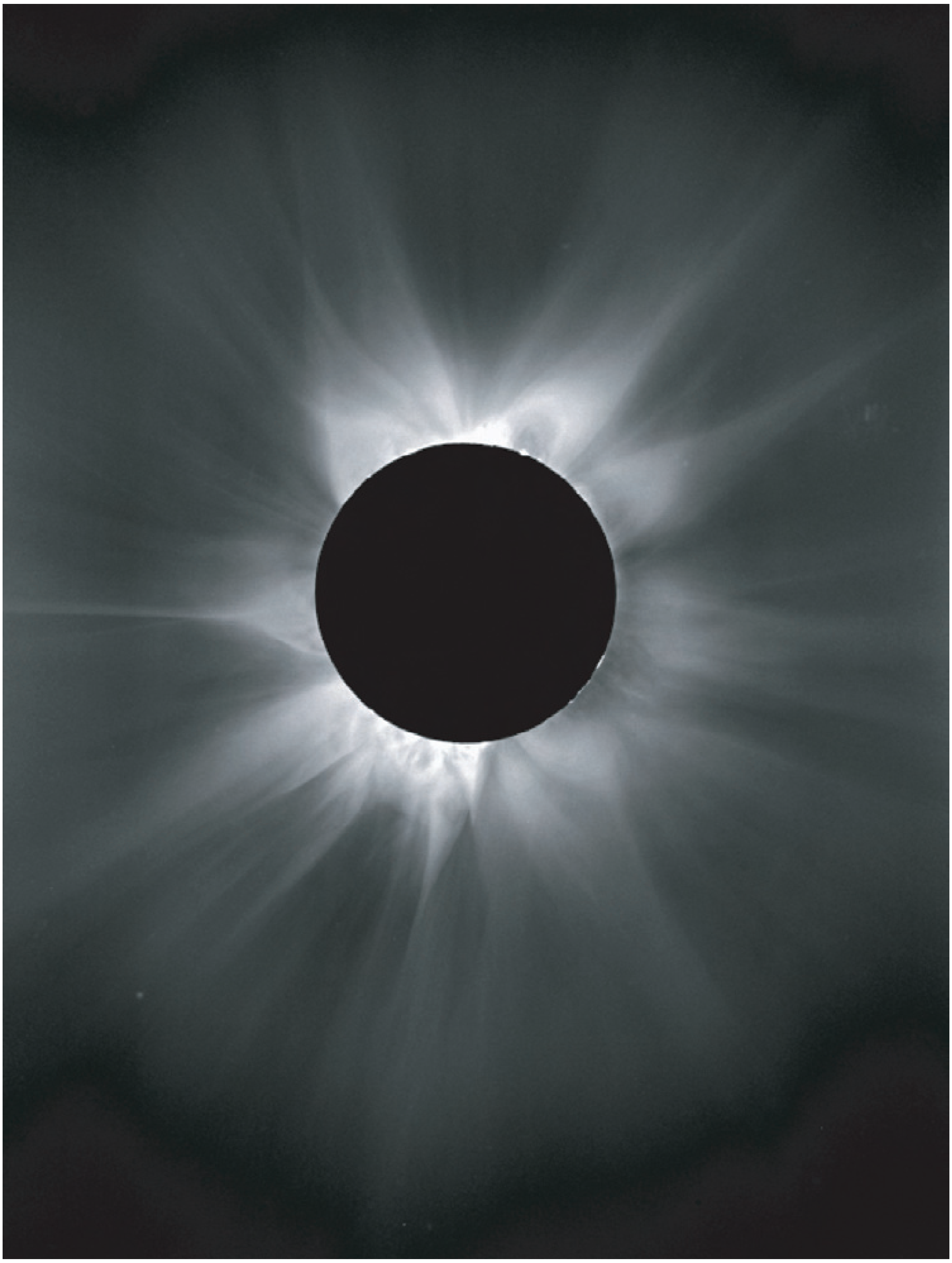
In addition, since the density within the corona decreases with height, its own brightness rapidly fades with increasing distance from the limb of the Sun, until it approaches the limits of practical detection: soon ten million, then a hundred million, then a thousand million times dimmer than the bright photosphere.

The second obstacle is the competing brightness of the sky itself, which no matter how clear and blue, is far brighter than the solar corona, and particularly in the sky immediately surrounding the Sun, which is precisely where the corona appears. Nor can we hope to catch a fleeting glimpse of the corona or the chromosphere just as the Sun dips below the horizon, or as it slides behind a cloud or the edge of a barn, for the brightness of the daylit sky around it will still defeat our every try.

Until fairly recently the only way to see the Sun's corona was the way it was first discovered: in the fleeting moments and within the restricted geographical bounds of a total solar eclipse. A total eclipse occurs, somewhere on our planet, about every year and a half; but as noted earlier, at a particular place, be it London or Topeka, Kansas, only very rarely.

During a total solar eclipse, the Moon—a quarter of a million miles away—blocks for a few minutes the bright light of the photosphere before it can reach and illuminate the atmosphere of the Earth. Through these rare windows of opportunity—most often in far away places with strange sounding names—we are allowed to see the outer atmosphere of the Sun in all its glory, against the background of a sky turned suddenly dark and filled with other stars.

For a few seconds of these few minutes, we can also catch a fleeting glimpse of the chromosphere as well, as a thin, red-colored layer just beneath the corona, as well as any large prominences that happen to lie at the edge of the Sun. Unlike the corona, the denser and cooler chromosphere and prominences shine by their own weak radiation, which is dominated in the visible spectrum by the same



An exquisite photograph of the solar corona, also taken in India during the total eclipse of the Sun that happened to cross that then independent nation on August 14, 1980. Magnetically-formed, bulbous-based coronal streamers—long described as resembling the petals of a dahlia—reach outward into space from both low and high solar latitudes, as is typical at the maximum phase of the 11-year activity cycle, when this image was made. Coronal streamers of the type seen here can be torn free of the Sun in the course of violent eruptions and thrown bodily outward as gigantic blobs of ejected coronal plasma into interplanetary space.

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red-colored emission from atomic hydrogen that colors the aurora borealis and australis. The chromosphere, brighter than and not as elusive as the corona, can also be observed on a routine basis, and over the entire disk of the Sun, without the need for an eclipse: using a spectrograph or narrow optical filters designed for this purpose. These optical devices accomplish this feat by isolating the sunlight in narrow spectral lines that are particularly bright in the chromosphere, such as the red emission line of atomic hydrogen mentioned above.

Limited observations of the inner corona, made without the need for an eclipse, have also been possible for more than fifty years, employing specialized telescopes called coronagraphs. These employ optical techniques to create, in effect, an artificial eclipse of the Sun within the telescope itself, and have been operated for decades from mountain-top observatories where the daytime sky is clearer and a darker blue. But until they could be carried into space—where the Sun is always shining and the sky is always black—coronagraphs on the ground could never replicate, in either extent or spatial detail, what one saw of the corona in the brief moments of natural eclipses of the Sun.

Today, coronagraphs carried on spacecraft monitor and observe the Sun's outer, white-light corona around the clock, day after day and year after year. They also provide images that in many ways surpass those obtained at solar eclipses or with coronagraphs on the ground. And since they operate continuously, spaceborne coronagraphs are able to identify and follow changes in the corona that elude the still photographs taken with eclipse cameras. In but one day a coronagraph mounted on a spacecraft above the Earth's atmosphere provides more minutes of coronal observing time than what could have been accrued at all the total eclipses of the Sun in the last 1000 years.

Extant photographs of the solar corona taken at eclipse—which began within a decade after Louis-Jacques-Mandé Daguerre's remarkable invention in 1839—comprise a valued collection of *snapshots*, taken a few years apart, of the evolving form of the white-light corona. But the high-resolution images from space—which became available in the early 1970s—provide a continuous *movie* of the outer corona that catches every change, fast or slow, including particularly the release and expansion of huge chunks of coronal plasma, called coronal mass ejections or CMEs that can directly affect the Earth.

The 40 ft-long telescope of California's Lick Observatory set up near Bombay at Jeur, India to observe the total eclipse of the Sun on January 22, 1898. The cumbersome, long-focus telescope used a 5-inch lens to project an image of the Moon 4 inches in diameter and the corona up to 10 inches across, on 18 x 22 inch glass photographic plates. A series of these were adroitly inserted and removed from the focal plane by hand, one at a time, in the dark of the eclipsed Sun, at this site within a deep pit dug beneath the striped tent. The telescope, called "Jumbo,"was taken to fifteen total solar eclipses on six continents from 1893 through 1932, each affording an opportunity of but a few minutes to see the fleeting corona of the Sun.

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Direct observations of the Sun from space has brought about an equivalent revolution in our understanding of the inner corona and the chromosphere, through round the clock observations of the Sun in the invisible ultraviolet and x-ray light which these regions emit. Since these incoming solar rays are absorbed in the high atmosphere, we are prevented from seeing the x-ray or ultraviolet Sun from the ground.

Telescopes in space that are capable of imaging the Sun in x-ray radiation see the inner corona, more than a million degrees hot, in the light of its own radiation. The familiar x-ray images employed by your doctor or at the airport differ in that they are not pictures of the *source* of x-radiation (in this case a high-voltage vacuum tube deep within the apparatus) but *shadow pictures* of your opaque bones or carry-on luggage, illuminated from behind by a point source of x-ray radiation.

X-ray images of the inner corona offer the great advantage of displaying the entire visible hemisphere of the Sun, as in a bird's eye view from above, as opposed to the more limited edge-on views seen at an eclipse. Moreover, sophisticated x-ray telescopes in space provide these images in extremely fine detail, like high-definition television.

Similar observations of the Sun made from space in the extreme-ultraviolet reveal the upper chromosphere and the transition zone above it in full hemispheric coverage and in fine detail.

As noted earlier, the temperature of the Sun's outer atmosphere rises rapidly with height. With increasing temperature the maximum emission from the region shifts toward shorter and shorter wavelengths. Radiation from the 10,000° photosphere, for example, peaks in the yellow portion of the visible spectrum; from the million degree corona it has shifted all the way into the far ultraviolet and x-ray region.

Thus by a judicious selection of wavelength, including the choice of specific spectral lines, one can isolate and observe different layers of the solar atmosphere, from the photosphere through the chromosphere and transition zone into the low corona: much as adjusting the focus on a pair of binoculars allows one to observe objects that are closer or farther away.

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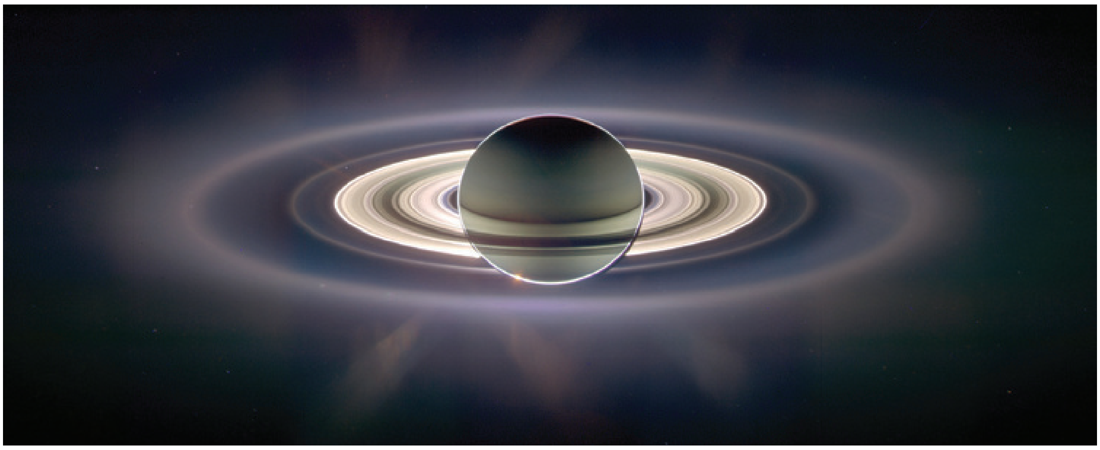

The Sun eclipsed by giant Saturn, seen from the Cassini spacecraft as it circled that cold and distant planet in 2006. The bright narrow ring that goes fully around the circular Saturn is photospheric light diffracted from the occulted Sun which lies behind it. Because the Sun is more than nine times farther from Saturn than from the Earth, it would appear much smaller in Saturn's sky than in our own; in this view, made from a relatively short distance from the planet, Saturn's disk appears far larger than the distant Sun hidden behind it. The dimly-lit night side of the planet is here illuminated by indirect sunlight reflected from its many extensive rings, some of which were not found before this image was obtained. Far in the distance, hardly visible and little larger than the specks of other stars is our own small pale blue planet. It can be found in the dark space between Saturn's outermost bright, fuzzy ring and the first, thin dimmer ring, closer to the latter, and at an angle corresponding to about 9:30 on the face of a clock.

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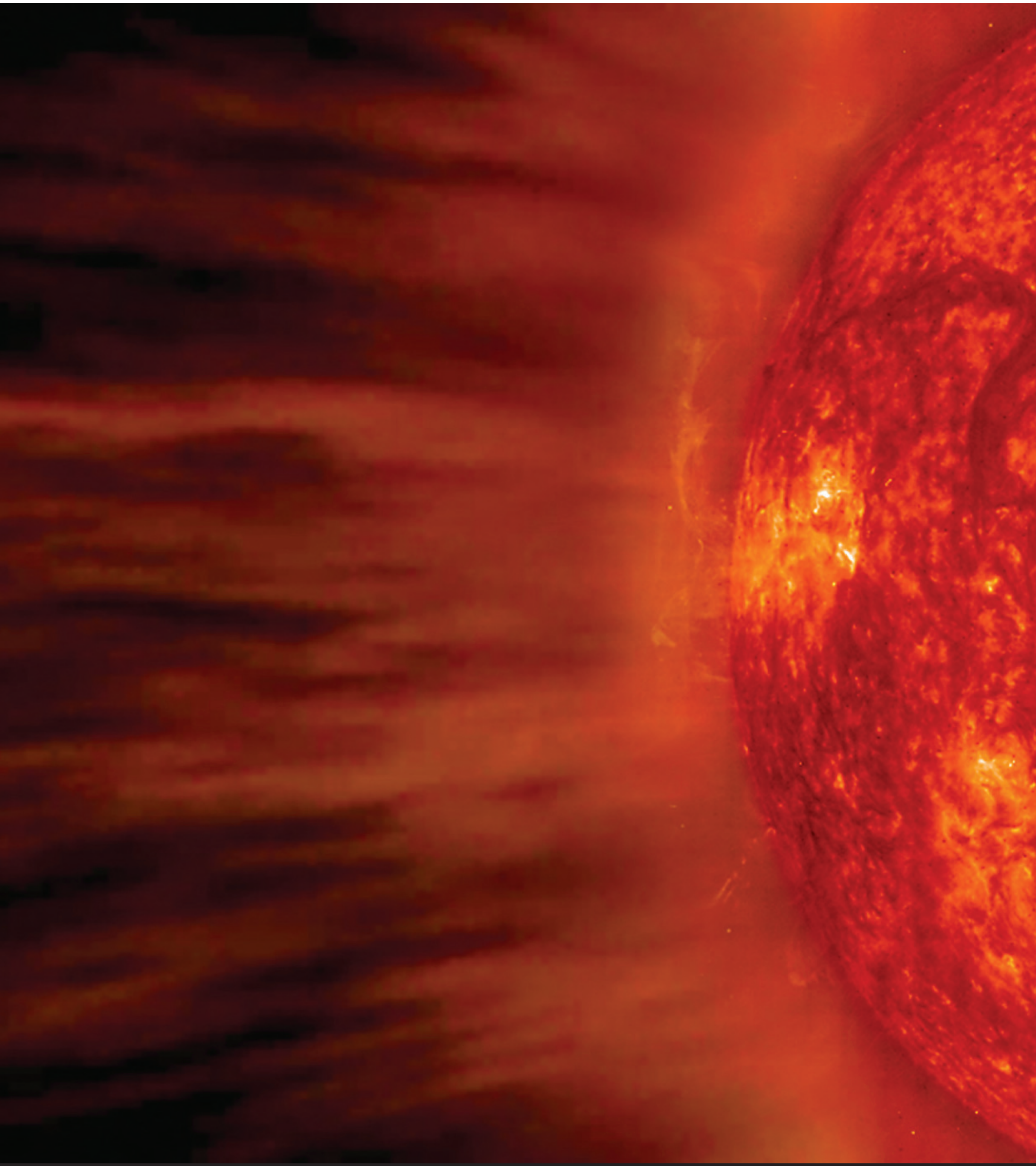

A computer-aided depiction of the outward flow of charged atomic particles from the Sun in the solar wind, shown above an actual image of the hot upper chromosphere, made in the far ultraviolet.