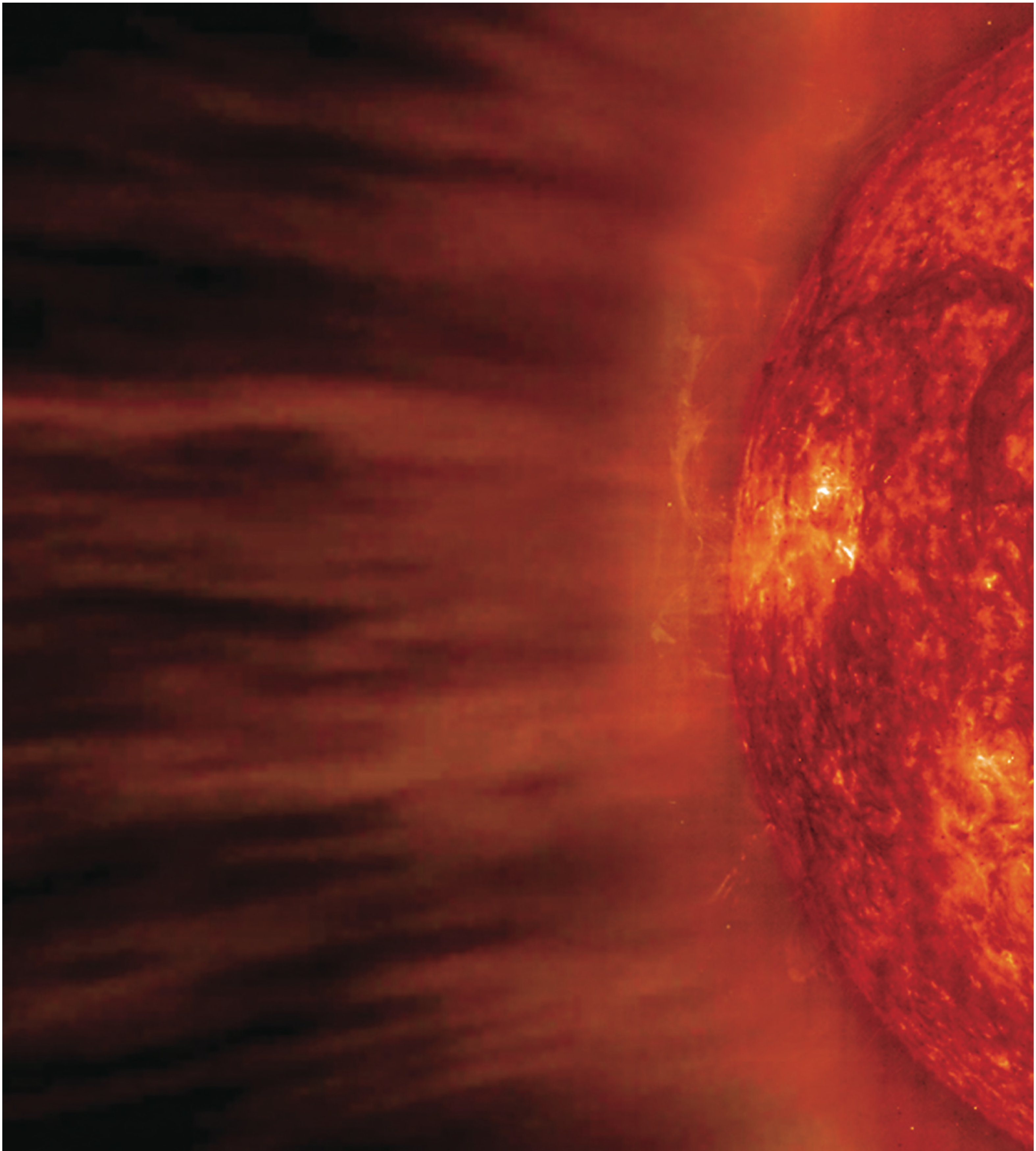

A computer-aided depiction of the outward flow of charged atomic particles from the Sun in the solar wind, shown above an actual image of the hot upper chromosphere, made in the far ultraviolet.

THE SOLAR WIND AND SOLAR VARIABILITY

The Solar Wind

A consequence of the extremely high temperatures found in the corona is a corresponding increase in pressure—as happens in a covered pan heated on the stove. In this case there is no lid, and the heated corona expands freely outward, pushing against the yielding, lower pressure of the interstellar gas.

This thermally-driven flow of ionized, charged particles—known as plasma—constitutes an ever present wind that carves out a cavity, called the heliosphere or realm of the Sun, in the surrounding interstellar medium.

Thus, in addition to heat and light the Sun also releases a continuous flow, called the solar wind, of atomic particles—protons, neutrons, electrons and ions of all the solar elements—that expands outward, night and day, in all directions everywhere. This never-ending flow of coronal plasma is of considerable significance for the Earth and the other planets. And so it has been for billions of years.

Notably absent in the solar wind that reaches the Earth, are neutrons: the fundamental atomic particles with neither positive nor negative charge which with protons are the building blocks of atomic nuclei. But although neutrons are present in great abundance on the Sun and are driven off with other particles in the solar wind, the lifetime of any one of them is so ephemeral—lasting, typically, no more than a few minutes before it decays—that most of them are gone by the time they reach the orbit of Venus.

The other particles continue on and on, as the Sun's principal contribution to the universe, filling every crevice of the heliosphere—beyond the dimmest reach of its light beams—with windblown seeds of itself. And they keep on coming, in seemingly endless supply, as from a magical dandelion. In but one second of this continual outpouring, the wildly extravagant Sun gives a million tons of itself away. And in the course of a year, almost 10^{13} tons.

With little to slow it down, the high-speed solar wind reaches the orbit of the Earth—after traveling 93 million miles—in but two days; and the slower wind in about four. At the Earth the average velocity of the streaming solar wind is about 225 miles per second. The fastest streams that reach the Earth blow at about 500 miles per second: a *thousand times* faster than a speeding bullet.

When it arrives at the Earth—however fast it moves—the solar wind is in terms of mass mostly nothingness, containing about 130 protons in a cubic inch, compared to the zillions of atoms and molecules in the air we breathe. And because it is so diffuse, were the fast moving solar wind plasma to blow against our face it would feel far more like a baby's breath than the blustery winds we commonly sense at the surface of the Earth. Even so, the solar wind plasma at the Earth is about 50 times more densely packed than the ambient conditions it will eventually meet outside the heliosphere.

Once past the orbit of the Earth, the solar wind plasma continues streaming outward at constant speed for more than a hundred times our distance from the Sun: well past the orbits of Mars, Jupiter, distant Saturn, and far away Uranus, Neptune and little Pluto.

Somewhere well beyond the planets it will reach the cold and darkened limits of the Sun's domain: the as yet unexplored boundary that marks the end of the heliosphere. Here, a long way from home, its initial force is so depleted by dispersal over so vast a volume of space, that the solar wind loses the upper hand. The weakened pressure of outward streaming plasma no longer exceeds that of similar but alien particles arriving from countless other stars. There, at the heliopause the solar and stellar winds will meet, though because of their differently oriented magnetic fields, they will seldom truly mix.

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Since it is composed of charged particles, the streaming solar plasma travels outward from the Sun still bearing the embedded (or "frozen in") magnetic signature of the place from which it came, carried with it like a trailing ribbon still tethered at one end to the Sun. Because the surface magnetic field of the Sun is organized into discrete patches of either positive (outward-directed) or negative (inward) polarity, the magnetic earmark of its place of origin is preserved in each stream.

The solar wind that streams outward in this way from equatorial regions of the Sun is divided by these differences in polarity into spatially discrete portions or sectors, which expand in width with distance from the Sun. Although the plasma flows radially outward, the open field lines that it brings with it—still attached to the solar surface—are shaped into a curved spiral by the 27-day rotation of the Sun. As the Sun rotates, sectors of different magnetic polarity in, above or below the equatorial plane, are swept across the Earth, like a spray of water from a revolving garden hose, exposing our own magnetosphere—for a week or more at time—to first one and then the other polarity, in a varying sequence of slow and fast plasma streams.

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At those times when the direction of the imbedded solar field opposes that of the Earth, we are more vulnerable to the impacts of incoming solar particles. Under these conditions, where the onrushing plasma makes contact at the Sun-facing "nose" of the magnetosphere the opposing magnetic lines of force merge and connect. There, through a process peculiar to highly-conducting plasmas called magnetic reconnection, magnetic energy from the Sun is efficiently converted to kinetic energy in the Earth's magnetosphere.

When this happens, the drawbridge is down and some of the energy of the onrushing solar plasma makes its way into our own magnetic field, with consequences that can perturb and disrupt conditions on the surface of the Earth.

As noted earlier, it takes several days for the solar wind plasma to reach the Earth. This means that by the time it arrives here, its place of origin on the Sun has already been carried by solar rotation more than halfway toward the right-hand or western edge of the Sun, soon to disappear from our view.

Were we standing on Jupiter—five times our distance from the Sun—the time between release and arrival would be that much greater. There, by the time the solar plasma arrives, the shooter has already escaped from sight, around the western limb of the Sun.

Sources and Characteristics of the Solar Wind

A great deal has been learned about the solar wind and its origins on the Sun since it was first postulated by Eugene Parker in 1958 and then confirmed, by direct measurements in space four years later, in 1962. In the forty-odd years since then, scores of spacecraft have explored and monitored the composition, velocity, embedded magnetic fields, and temporal fluctuations in the flow, employing ever more sophisticated sensors.

To accomplish this, solar wind detectors have sampled and monitored conditions within the heliosphere from well inside the orbit of Mercury to far beyond that of Pluto.

Ulysses is the first spacecraft to explore the solar system above and below the plane of the Earth's orbit: truly the *terra incognita* of the solar system before the itinerant spacecraft was launched in early October, 1990. Since that time *Ulysses* has traced out successive six-year orbits around the Sun, passing over both poles of the star to sample and measure the solar wind in these lesser known regions and to observe from above, the flow of solar plasma from the Sun's polar areas.

With the help of *Ulysses*, *in situ* measurements of the solar wind combined with observations from space of the outer corona—where the solar wind is shaped and directed—have allowed scientists to identify the specific regions in the corona where solar wind streams of various kinds originate and the sources of perturbations in the streams that reach the Earth.

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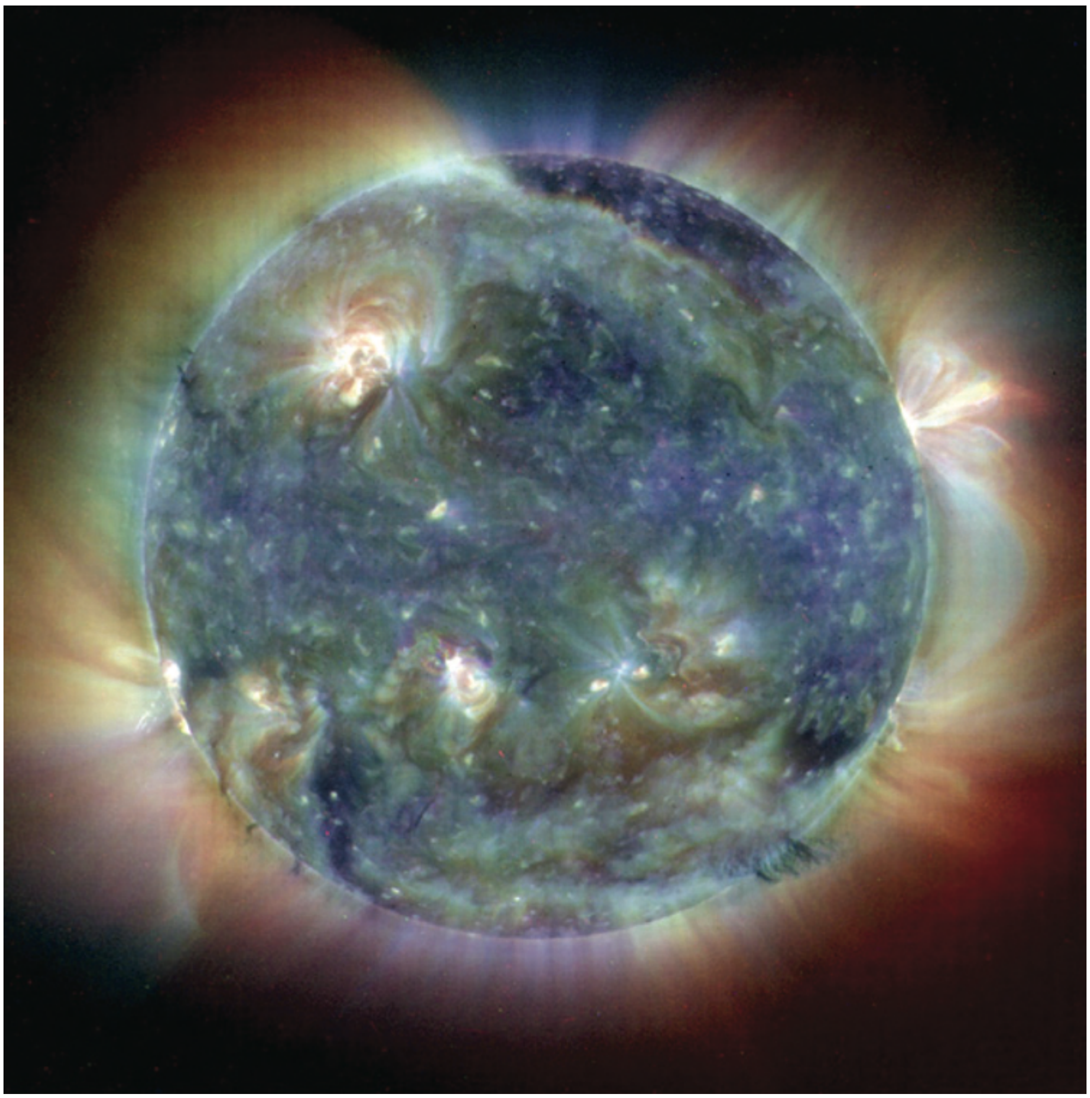
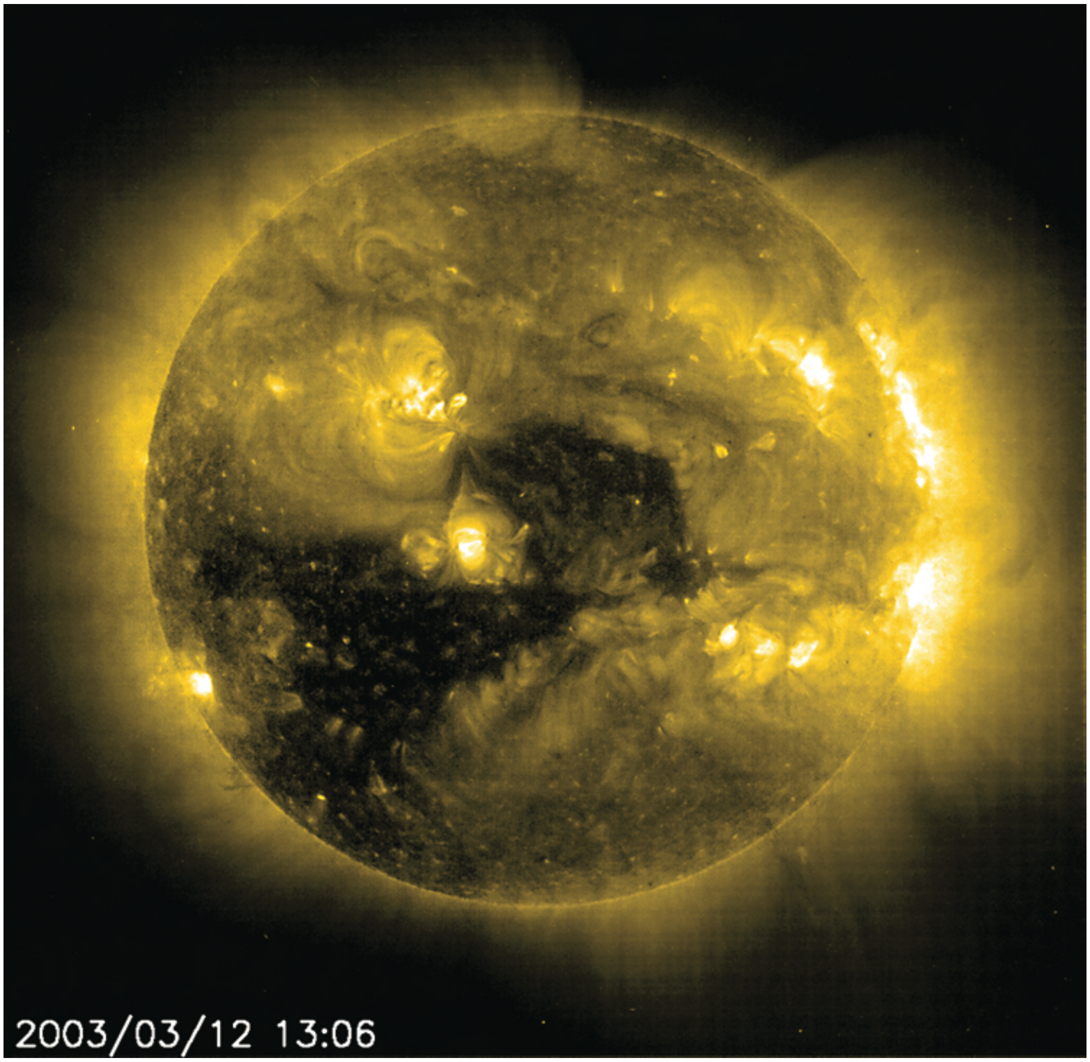


A melded view of solar radiation emanating from the transition region of the outer solar atmosphere where local temperatures are in the hundred-thousand degree range, and from the million-degree lower corona, made by combining images of the Sun in the EUV and x-ray regions of the spectrum. Of note is the association of hotter, brighter active regions with closed magnetic loops; and coronal holes and bright points in the transition region with depleted portions in the corona above them.



The Sun seen in fine detail in the very short wave, x-ray region of the spectrum. Radiation at these invisible wavelengths originates in the lower corona, where temperatures are measured in millions of degrees Fahrenheit. The hot spots evident as bright features identify regions of concentrated magnetic fields: the origins of solar flares and coronal mass ejections, and the foot-points of coronal streamers which extend beyond what is seen here into the higher corona. Areas of lower electron density that appear as extended dark areas, known as coronal holes, are the loci of open magnetic fields and the origins of high speed streams in the solar wind. Within their boundaries, looking much like the lights of cities seen from space, are highly-concentrated, bright points of coronal x-ray emission.

As noted earlier, two types of solar wind—different in speed, composition and place of origin—blow outward from the Sun.

The so-called slow-speed solar wind has an average speed of about 200 miles per second and is made up of ions common to the upper corona of the Sun, from whence it comes. The sources of the slow wind are coronal streamers, which are associated with strong magnetic regions in the Sun's lower atmosphere. In years of minimal activity they are found only in lower solar latitudes. When the

Sun is more active coronal streamers appear at both low and high latitudes, and there are more of them. Because of this, slow-speed steams in the solar wind are more prevalent in years near the maxima of the 11-year sunspot cycle.

SOLAR WIND SPEEDS COMPARED WITH OTHERS

	MI/SEC	MI/HR
A Speeding Bullet	0.4	1440
Slow Solar Wind, average speed	200	900,000
High Speed Solar Wind Streams	470	1,700,000
Fastest Solar Wind	560	2,025,000
Speed of Light	186,000	670×10^6

The high-speed streams in the solar wind race outward at speeds two to three times faster, and their elemental composition is more representative of the inner corona and transition zone.

Their origins can be traced to extended regions on the Sun where there are few sunspots and other signs of magnetic activity. When seen in x-ray images of the inner corona these "quiet" regions appear as dark vacancies or "holes" in the brighter corona around them: like clearings in an aerial view of a forest, which in this case is made up of closely packed coronal loops; or as bald spots at the poles of the Sun. In the outer corona they appear as regions of very low density, largely devoid of coronal streamers.

Within these extended zones of solar inactivity, magnetic lines of force extend radially outward like blades of tall grass above the surface of the Sun, defining open magnetic field lines that are tied to the star only at their base. The closed field lines which connect regions of opposite magnetic polarity in solar active regions restrict the release of hot plasma from the corona, producing the low-speed streams in the solar wind. In contrast, areas of open magnetic field lines present little opposition, allowing solar plasma in the transition zone and corona to escape the Sun at much higher velocities.

In years around minima of the 11-year sunspot cycle, extensive coronal holes cover the polar caps of the Sun, extending downward in places to lower solar latitudes.

Solar Variability

All solar fluctuations that disturb the Earth can be traced to the effects of the strong solar magnetic fields that thread their way through the photospheric surface and into the middle and outer atmosphere of the star. Indeed, were the Sun to rid itself of all magnetic fields, it would hardly vary at all: leaving but a big light bulb in the sky, slowly burning itself out.

Solar activity is a general term used to describe the nature and extent of solar magnetic fields. The venerable and most common index by which it is described relates to the number of sunspots visible on the disk of the Sun at any time. Since 1848, astronomers around the world have for this purpose employed a universal but arbitrarily-defined index, called the Wolf sunspot number, or more commonly, sunspot number, which endeavors to correct for unavoidable differences in solar telescopes, observing conditions and human observers.

The sunspot number defined in this way is calculated daily, but the most common denomination—the $20 bill of sunspot numbers—is the annually-averaged value. When these are displayed as a time-series graph, a cyclic rise and fall is readily apparent, defining an elastic "cycle" that varies in length from nine to thirteen years, with a mean value of about eleven.

Individual cycles, which by convention run from one sunspot minimum to the next, are identified by number, beginning arbitrarily with the cycle (#1) which extended from 1756—when Thomas Jefferson was a boy—until 1766. The most recently completed cycle, #23, which reached a maximum in 2001and a minimum in 2007, was as always, immediately followed *(The King is dead. Long live the King!)* by cycle #24 which should maximize in about 2013. Through history, the 11-year sunspot cycle has enjoyed an almost hypnotic appeal to professionals and amateurs alike, scrutinized chiefly for with what it might be correlated. Needless to say, its statistical examination is a finely-plowed field.

The nearly random variation in the lengths and amplitudes of cycles, and the existence of periods when for decades the number of sunspots falls to very low levels, tell of an internal mechanism within the Sun that is hardly the precise ticking of a clock. If your electrocardiogram looked anything like the graph of annual sunspot numbers, your doctor would have a very worried look on his or her face.

The underlying 11-year cycle is hardly detectable in weekly or even monthly averages, where it is more than masked by short-term variations of greater magnitude. These are imposed in large part by the Sun's rotation, which continually brings different faces of the Sun into view, and by the birth, evolution and fading away of different active regions.

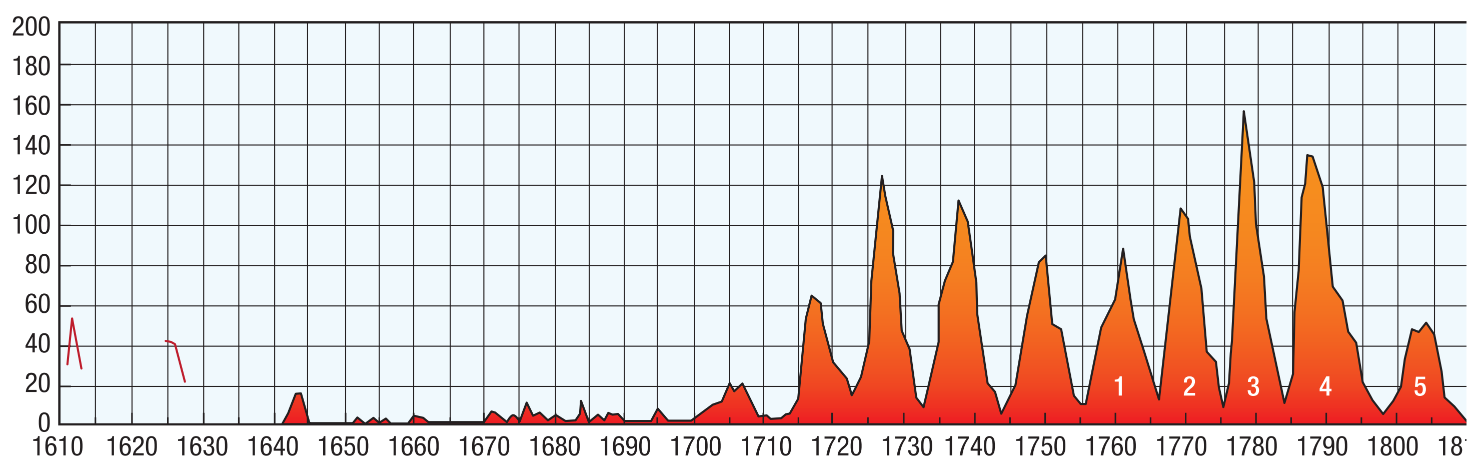
All of these variations have been known for a long time, as has the revealing fact that sunspots doggedly adhere to fixed rules of placement and magnetic polarity, following the same time-worn patterns and well-worn tracks, from cycle to cycle and century to century.

Sunspots generally appear in pairs, oriented along roughly E-W lines: a leader spot of one magnetic polarity, followed by another, just behind it, of the opposite sign. Sunspots are also concentrated at any time within two bands of solar latitude, one in the northern and one in the southern hemisphere, each of which migrates toward the equator in the course of the 11-year cycle. The magnetic polarities of the leading and the following spot are of opposite sign in the two hemispheres, and this, too, switches on cue, at the start of each new 11-year cycle. The same is true of the two polar regions of the Sun, which reverse polarity with each new 11-year cycle.

Thus the time to complete one full solar magnetic cycle—from one polarity to the other, and back again—is about 22 years: which is fast indeed for an object so large and massive. In comparison, the magnetic field rooted in the molten core of our little solid Earth has reversed its polarity but three times in the last five million years, at highly irregular intervals, and through processes that happen far more slowly and far from synchronously at the two poles. How does the Sun make its switch so fast, and where and how does it happen?

Why the Sun Varies

The answers lie in the fact that the Sun has no long-lasting imbedded field like that of the Earth. What we observe on the surface of the star is a conglomeration



The observed year-to-year variation in the sunspot number (a measure of the number of dark spots and sunspot groups seen on the white-light Sun, corrected for observing conditions) spanning the period from the earliest use of the telescope through 2007. Shown for each year is the mean annual value of daily numbers, which vary considerably from day-to-day.

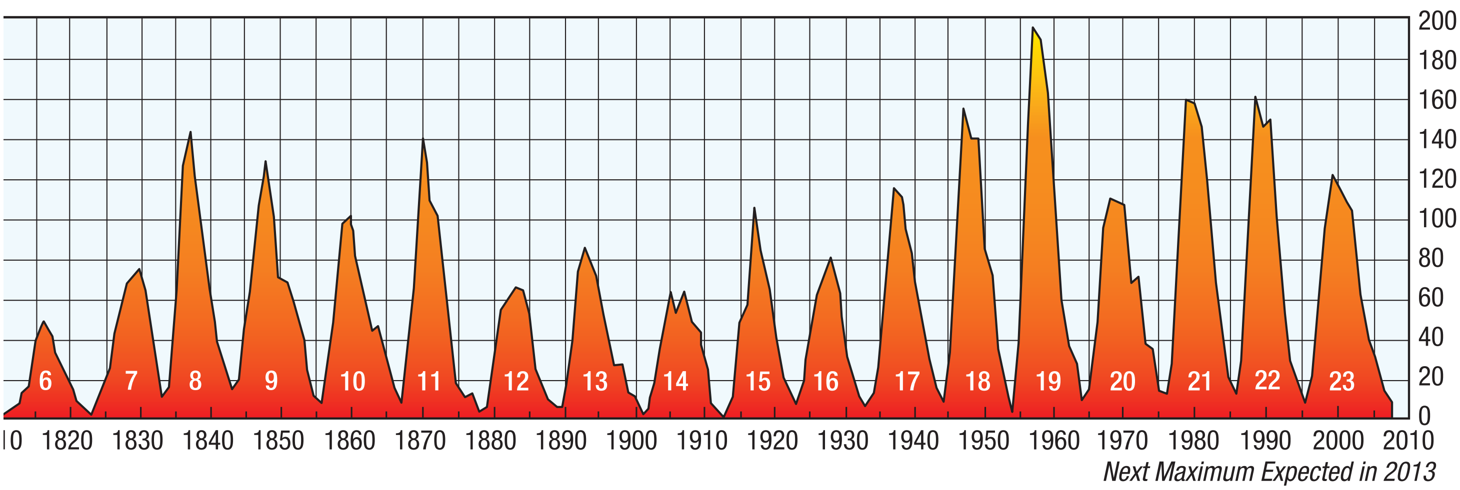
of superficial fields that are only skin deep: the transitory manifestations of magnetic fields that are continuously generated deeper within the star and carried upward to the radiating surface.

The so-called solar dynamo, which converts polar to toroidal magnetic fields within the Sun, operates on the same basic principle as the huge dynamos in public power plants that convert kinetic energy into electric currents and magnetic fields. But to fit what we know of the ritualistic behavior of sunspots, the solar mechanism must also orient, organize and then release the newly-created magnetic fields in ways that keep them in line and in step, like soldiers on the march, in cadence with non-stop drum beats of eleven and twenty-two years.

Some questions remain, but we now think we know what fuels the solar dynamo, how it operates, and where within the Sun it does its work, initiating a chain of events that ultimately perturbs conditions on our planet and the daily lives of all who live here.

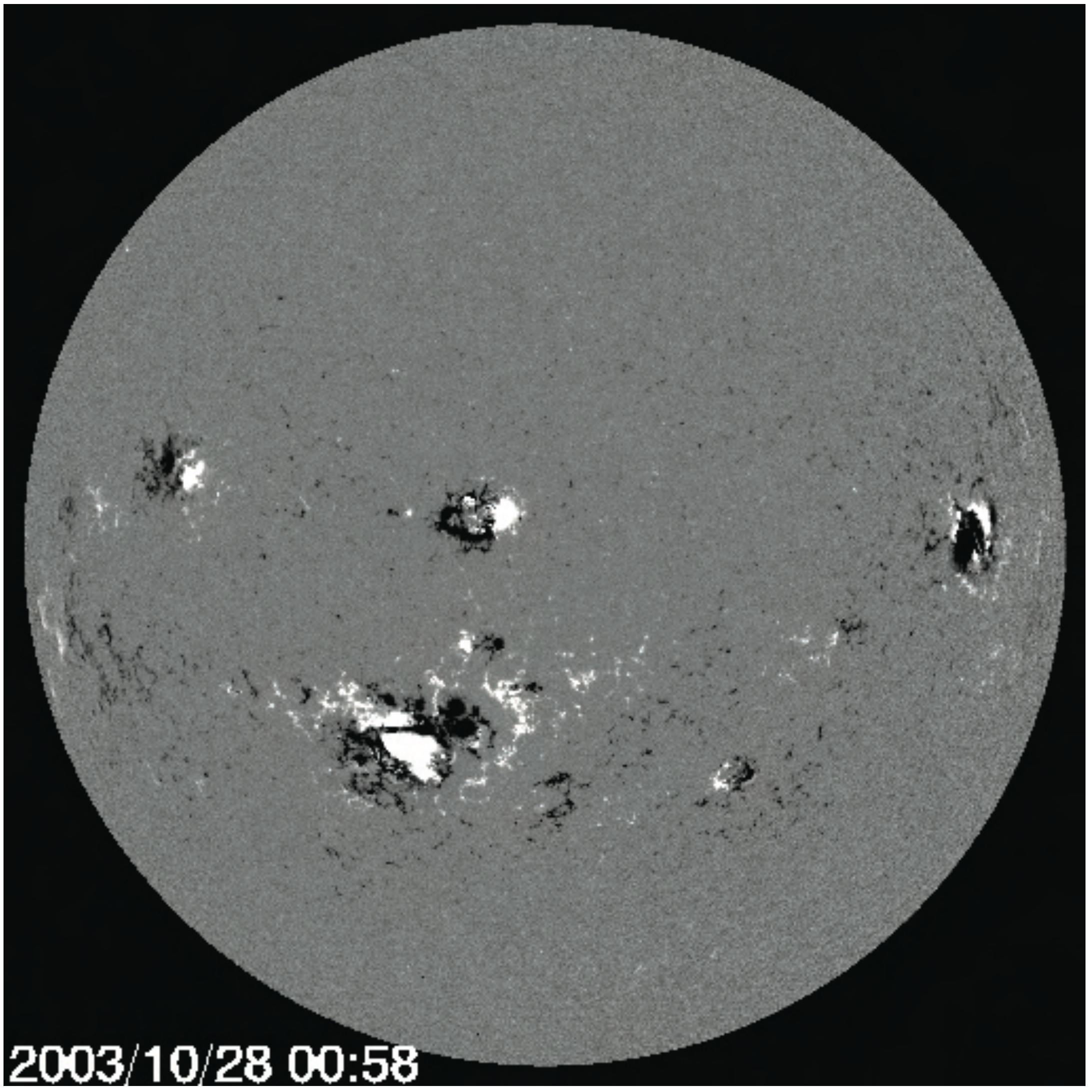
Deep within the hot interior of the Sun, the motions of electrically-charged atomic particles within the solar plasma continually generate incipient magnetic fields, much as the motions of molten metal deep within the Earth give birth to the Earth's magnetic field. But there the similarity ends, for conditions within the Sun and the solar plasma are far more fluid, turbulent and transitory.

When upwardly mobile magnetic fields generated within the Sun arrive at the boundary that separates the spherical, radiative core of the innermost Sun from the deep shell of convection that lies above it they enter a different world.



Evident is the well-known cycle of about eleven years, and obvious trends in the longer-term, overall level of solar activity. The period of suppressed activity between the mid-1600s and about 1715 is known as the Maunder Minimum, a feature that is also evident in other records of solar behavior.

There in a thin transition layer called the tachocline they come in contact with the strong shearing force that arises from the different rates of rotation of these two internal regions: the one a rigidly rotating ball (the radiative core) and the other an independently-rotating spherical shell (the convection zone) that spins at a different speed just above it. The shearing force at this interface flips and re-orients what were originally N-S oriented fields into those that are organized in the E-W direction, creating closed, magnetic hoop-like rings within the convective zone which lie in planes parallel to the Sun's equator.

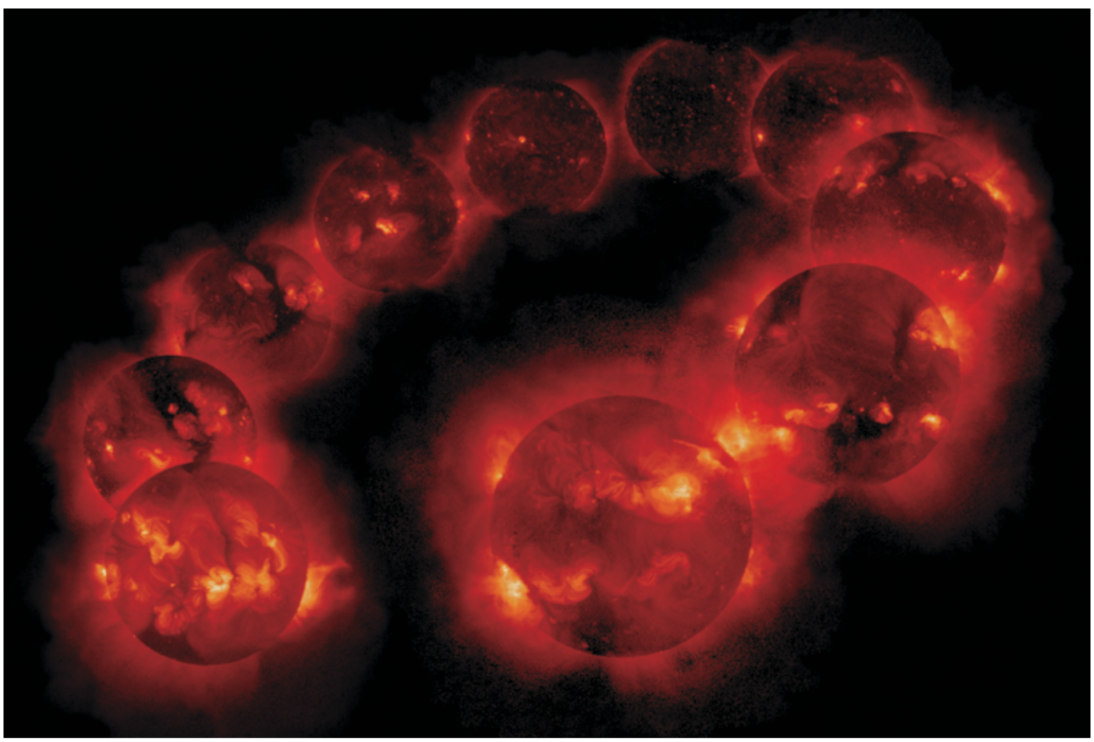


A magnetic picture or magnetogram of the solar photosphere made (from 93 million miles away!) on October 28, 2003 showing regions of strong magnetic polarity. White portrays what is conventionally called *positive* (or *north*) polarity, black *negative* (or *south*) polarity. As we see here, magnetic regions (which correspond to regions of sunspots and other manifestations of concentrated solar activity) are made up of adjacent parts of opposing magnetic polarity which are confined within two distinct belts of solar latitude.

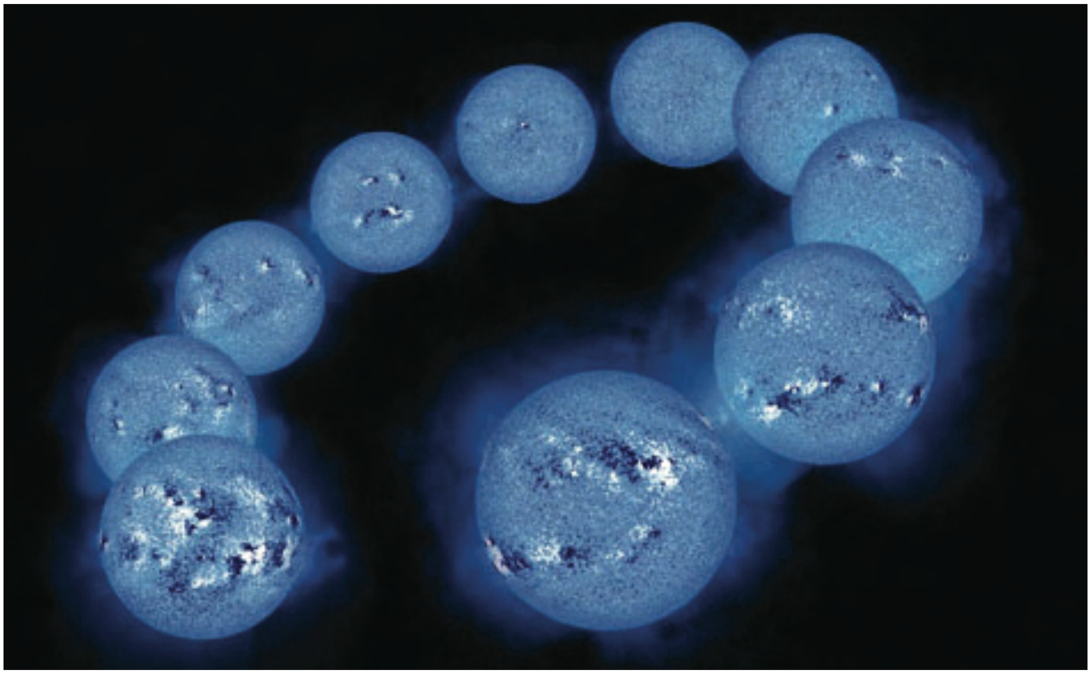
Magnetic pressure pushes these toroidal rings of magnetically-organized plasma upward and outward through the convective zone, to rise like smoke rings, one after another, some into the northern hemisphere of the Sun, others into the southern.

When a portion of any one of these buoyant rising rings of bundled magnetic lines of force comes in contact with the overlying photosphere, the toroid is at that point severed and pulled apart, exposing two ends of opposite magnetic polarity, which emerge as oppositely-polarized regions of surface magnetic activity and most visibly as sunspots.

The number of toroidal magnetic rings released at the base of the convection zone varies in a cycle of about eleven years. Due to the way they were created, the configuration of the magnetic lines of force in rings that approach the photospheric surface in the northern hemisphere of the Sun is opposite in any 11-year cycle to those that take the southern route. The result is a 22-year cycle in the characteristics of magnetic activity in pairs of sunspots in either hemisphere. In one 11-year cycle, as at the poles of the Sun, the polarity of the eastward (or leading) spot of a pair is positive and the westward (following) spot is negative in one hemisphere, and opposite in the other. In the next cycle these conditions are reversed.



Ten years in the life of the Sun, spanning most of solar cycle 23, as it progressed from solar maximum to minimum conditions and back to maximum (lower left) again, seen as a collage of ten full-disk images of the lower corona made in x-ray radiation. Of note is the prevalence of activity and the relatively few years when our Sun might be described as "quiet".



Progress of the Sun through the ten-year period encompassed above, in this case as recorded in corresponding full-disk solar magnetograms that portray magnetic fields of positive and negative magnetic polarity on the surface of the Sun. The two polarities are depicted as either white or blue, with intensity proportionate to magnetic field strength.

Short- and Long-Term Changes in Solar Activity

Recent attempts to do this, based on dynamo models, have ventured testable predictions of when the present 11-year solar cycle (#24) would start and end and how strong it will be. Time will tell, but if proven correct, this could mark a major turning point in our ability to foresee and prepare for many of the societal impacts of year-to-year solar changes.

More difficult to reproduce in dynamo models are the slower and possibly systematic changes, spanning decades to centuries, which are evident in the long record of historically-observed sunspots and in indirectly-obtained proxy data that cover much longer spans of time.

Through the first half of the 20th century, for example, the total number of sunspots observed in successive 11-year cycles steadily increased, in the manner of an amplitude-modulated radio wave, as though the Sun were entering a longer period of higher and higher solar magnetic activity. As well it may have done, peaking, perhaps with cycle #19, as we see in the graph of annual mean sunspot numbers at the bottom of pages 52 and 53.

There have also been extended periods in which the peak amplitudes of successive 11-year cycles were consistently and severely depressed. An example is the period of several decades at the turn of the 18th century, when for several 11-year cycles the number of sunspots dropped to less than half what it was both before and after, and the cycle lengths were unusually irregular. A pronounced drop of a similar amount characterized annual sunspot numbers in three successive decades at the turn of the 20th century.

Most pronounced in the historical, telescopic record of sunspot numbers was the 70-year period from about 1645 to 1715, during which time the total number of sunspots that were observed and recorded was not that much greater than what are seen in a *single year* of high solar activity today.

This latter episode was later named the Maunder Minimum, and one that preceded it, running from about 1450 to 1540, the Spörer Minimum, after E. Walter Maunder and Gustav Spörer, the British and German astronomers who in the late 1880s called attention to the first of these curious anomalies. They were far from the first nor the last to do so, however. The dearth of sunspots between about 1645 and 1715 (which happened to coincide precisely with the reign of Louis XIV, the *Sun King*) had in fact been repeatedly pointed out during the years when it was happening. But it had been largely forgotten and probably discounted following Schwabe's remarkable discovery in 1843 of a 10- or 11-year cycle in annual mean sunspot numbers, which seemed to describe the Sun more nicely as a highly regular and strictly periodic star.

The Maunder Minimum might be considered an artifact in the historical record of telescopically-observed spots on the Sun, were it not that it also appears as a time of dramatic drop in the number of reported aurorae, and as a similar gap in naked-eye sunspots documented in those years by court astronomers of the contemporaneous *Qing* dynasty in China. More important, the Maunder and Spörer Minima stand out as dominant features of the tree-ring record of carbon-14, following seven other similar events—each 50 to 150 years long—that preceded them in time, and as similar features in the beryllium-10 record taken from polar ice cores.

Solar Explosions and Eruptions

Far and away the most dynamic and spectacular changes that occur on the Sun are the short term eruptions and explosions in its outer atmosphere that come and go in but a few minutes, a few hours, or at most a day. These include intensely bright, explosive flares; the eruptions and annihilations of towering solar prominences in the chromosphere and corona; and the expulsion of whole parts of the corona in the form of coronal mass ejections, or CMEs.

The occurrence of these three distinctive types of violent and often-related events is very much affected by the phase and magnitude of the Sun's 11-

year solar of activity. All involve the sudden release or exchange of energy, in massive amounts; and all, not surprisingly, involve the interactions of strong magnetic fields.

In years when the Sun is most active small flares occur somewhere on its surface every minute, and CMEs of one size or another are expelled from the corona at an average rate of three or four per day. In years of minimum activity these numbers fall dramatically.

Explosive Solar Flares

Solar flares appear as sudden and intense brightenings in highly-localized regions on the surface of the Sun: as though a lighted match had been dropped into a puddle of spilled gasoline. The initial and brightest part of the ensuing whoosh of light usually lasts but a few minutes, and the sudden event will run its course, on average, in less than half an hour. Some of the effects on the Earth are almost immediate. Others last for several days.

In the largest solar flares, the amount of energy released on the Sun from a relatively small region and in so short a span of time is far beyond all earthly experience.

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The asteroid that struck the Earth about 65 million years ago—marking the transition between the Cretaceous and Tertiary periods of geologic history—dealt, without doubt, one of the hardest blows our little planet has ever felt: so momentous that that single event is believed responsible by many scientists for the contemporaneous extinction of the dinosaurs. To produce this extraordinary impact, the asteroid must have been at least five and one-half miles in diameter, as dense as cast iron, and traveling at the moment of impact at about 45,000 miles per hour. Nevertheless, the energy released in that Earth-changing collision was still about 100 times less than what is released on the Sun in a single, very large flare.

As another comparison: The energy released in August of 1945 in the atomic bombs detonated over either Hiroshima or Nagasaki was equivalent to about 20,000 tons of TNT. A single hydrogen bomb—the next step toward destructive awfulness—can unleash the explosive power of *several thousand* atomic bombs. In contrast, the energy released in a large solar flare—of the sort that exploded on the limb of the Sun on Halloween in 2003—was equivalent to several hundred hydrogen bombs detonated all at once at the same place. The internal temperature sustained for a few minutes within the explosion can be for any flare as high as that in the innermost core of the Sun: more than 20 million degrees Fahrenheit. The area on the Sun in which a large flare is concentrated, though a miniscule fraction of the total solar surface, can equal the surface area of half of the Earth, with a vertical extent of about 6000 miles: nearly as high as the Earth is wide.

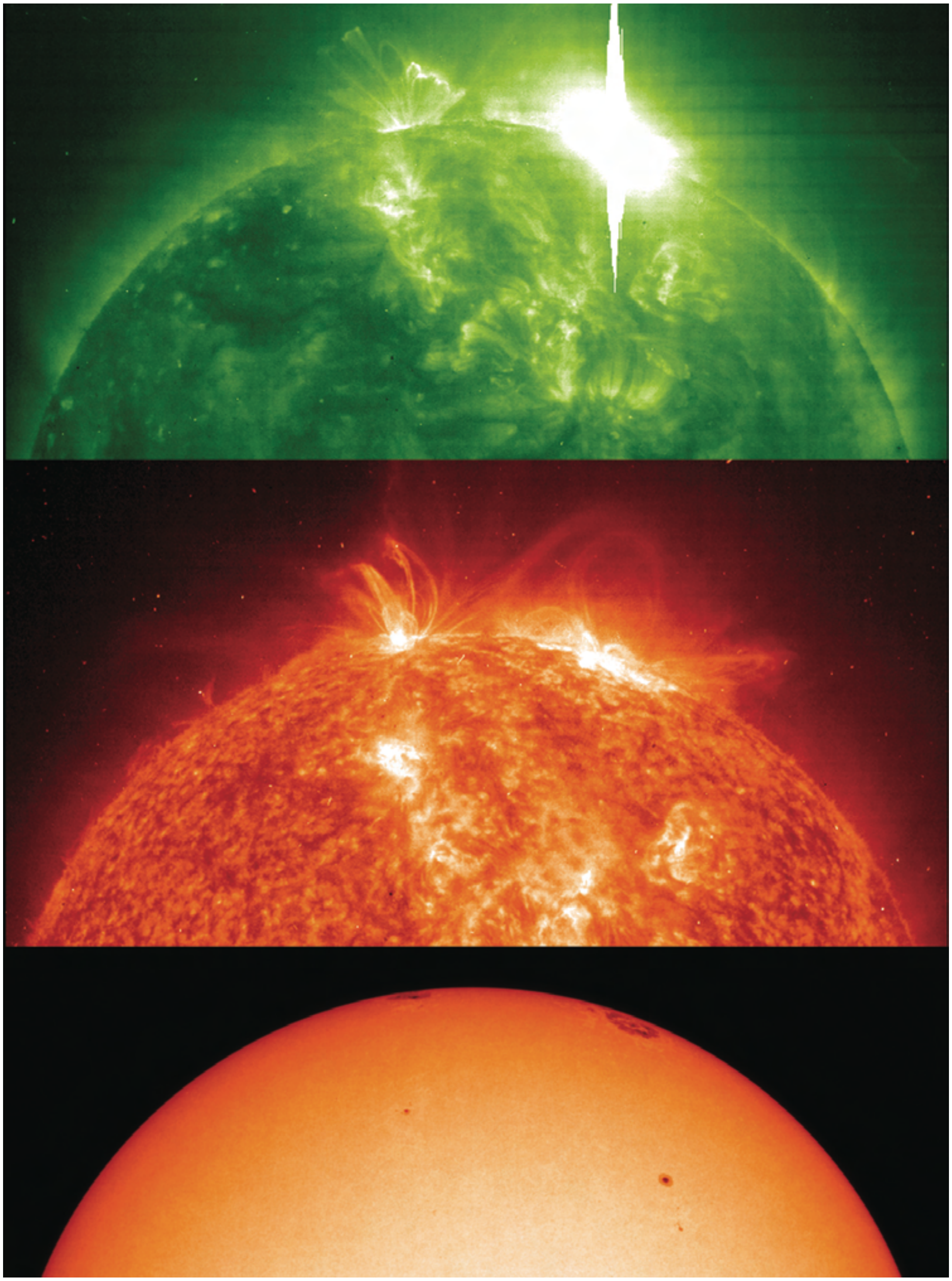
Most solar flares seem to be initiated in magnetic loops of the lower corona, and most of the immediate, ensuing action takes place above the photosphere in the chromosphere and transition zone. In these two intervening regions of the solar atmosphere the sudden and overwhelming impulse of energy—downward from the corona—triggers immediate responses in the form of bursts of radiation and particle acceleration.

Major flares occur only in magnetically-active regions on the Sun: in the distinctive and often snarled and twisted magnetic fields of complex sunspot groups. Their precise points of origin are most often found in places of magnetic confrontation and conflict where oppositely-directed field lines come into contact with each other. When this happens, the magnetic field lines can be severed, reconnected or re-formed, through processes that convert some of their huge store of magnetic energy into heat, radiation, and the acceleration of atomic particles in the local plasma.

The tremendous amount of radiative energy that flares emit is distributed over the full breadth of the electromagnetic spectrum: from gamma-rays to x-rays to ultraviolet to visible to infrared and radio waves. When a large flare occurs on the Sun it can be detected by instruments ranging from x-ray telescopes to radio receivers.

The high-energy x-rays, gamma rays, and far ultraviolet radiation from this blast of converted energy are sprayed out from the source of the flare in all directions, and strike the upper atmosphere of the Earth with no warning at all, since they too, travel at the speed of light. The heavier atomic particles that receive the most energy can be driven from the Sun at velocities of up to almost half the speed of light, to arrive at the Earth in but fifteen minutes, which is but seven minutes after the flare is first seen.

Slower particles of lower energy will strike the Earth within hours to a few days later, but they can affect the Earth in only minor ways, compared to the potential damage done by the more energetic solar protons in the initial eruption or the effects of CMEs. Radiation and heavy particles from large flares pose a direct hazard to exposed spacecraft and astronauts whose travels take them beyond the protective shields of the magnetosphere and upper atmosphere.

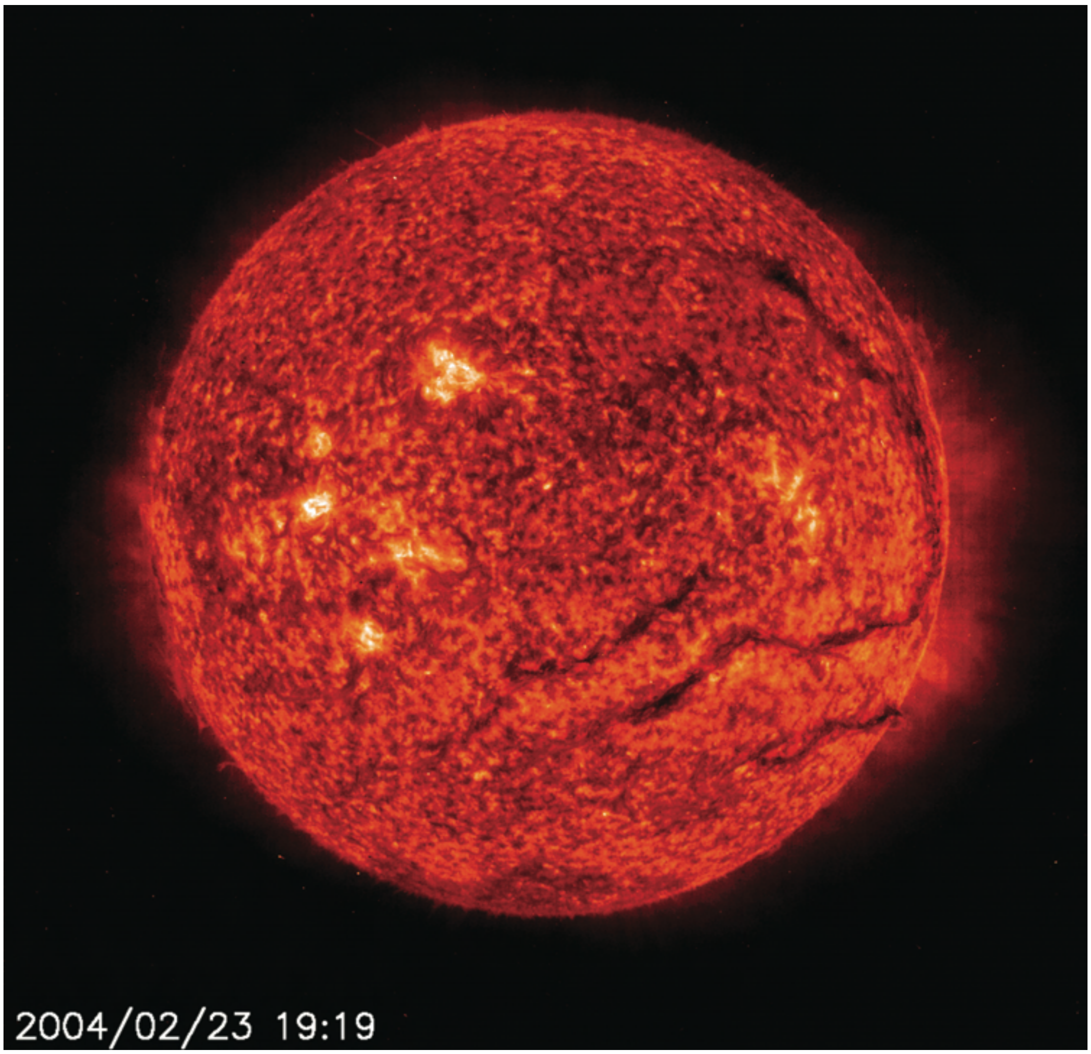


Three images showing the eruption of an extremely energetic solar flare at the limb of the Sun, taken at the same time on November 4, 2003. Shown, from bottom to top, are the white-light photosphere; the upper chromosphere (seen in the extreme ultra-violet); and in x-ray wavelengths, the lower corona (from which most of the flare's prodigious store of energy was released.) The associated magnetic region is visible in the first of these as a cluster of large sunspots being carried over the east edge of the Sun by solar rotation. The actual size of the associated active region is revealed in the two higher images as an extensive group of very large magnetically-active regions.

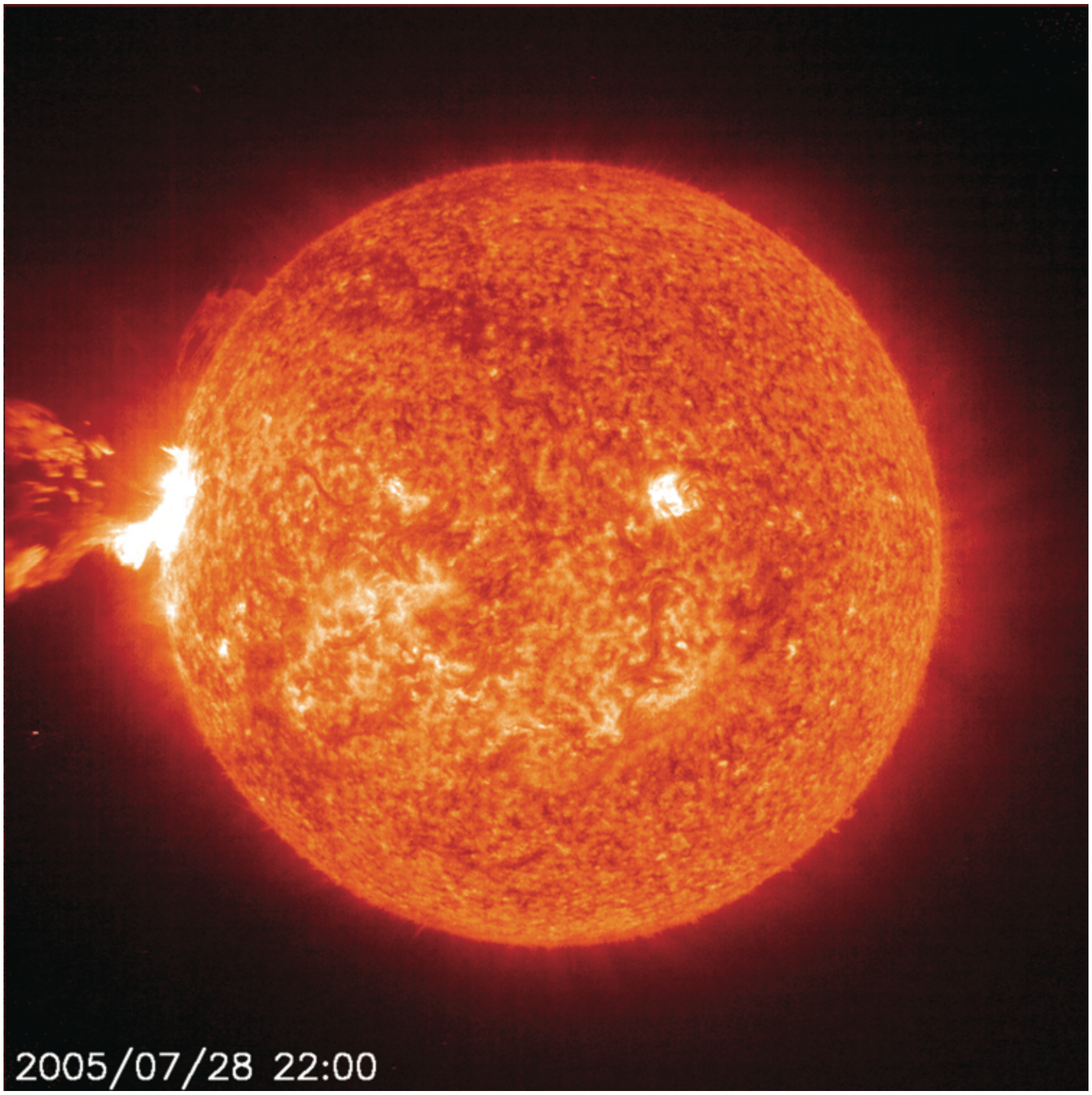
Solar Prominences and Filaments

Some of the magnetic lines of force that reach upward from regions of particularly strong sunspot magnetic fields are able to carry cooler chromospheric material with them into the hotter corona, where it is magnetically insulated and held aloft for a time, in the form of extended clouds called solar filaments.

When seen in visible light at the edge, or limb of the solar disk, as in a coronagraph or when the Sun is eclipsed by the Moon, these extensions of



The active Sun seen in the EUV on February 23, 2004, displaying hotter, magnetically-active regions and cooler, darker filaments. Dark filaments of this kind, were they seen at the edge of the Sun, would appear as long, elevated clouds extending above and beyond its curved limb. They can persist for several weeks and are composed of hot chromospheric material held aloft in the less dense and far hotter corona by arched magnetic field lines, defying the force of solar gravity and the fundamental principle of heat transfer. Were it straightened out, the sickle-shaped, longest of these would cover nearly four times the distance that separates the Earth from the Moon.



Solar rotation carries an active region into view on the east limb of the Sun, revealing the initial lift-off of a newly-spawned coronal mass ejection. In time, as it speeds outward into interplanetary space, the CME will expand to a size larger than the Sun itself. This view of the chromosphere, made in the far ultraviolet light of ionized helium, shows the solar plasma at a temperature of about 100,000° Fahrenheit, ten times hotter than the spotted, white-light photosphere which lies just beneath it.

chromospheric material, aptly called solar protuberances or prominences, appear in varied sizes and graceful shapes—sometimes resembling the handle of a Sun-sized teacup. Under these circumstances they stand out against the dim white of the corona as brighter features which are distinctively red: the pure color of light emitted by excited hydrogen atoms.

When we look at the disk of the Sun in the red light of hydrogen in the chromosphere, the same prominences—now seen from above—appear not brighter but *darker* than the surrounding disk, as worm-like dark filaments that are both cooler and denser than most of the other material around them.

When seen from this perspective it is obvious that the often sinuous forms of solar filaments follow the course of the neutral dividing line that separates regions of opposite magnetic polarity in solar active regions: like a referee who with arms extended, attempts to hold opposing magnetic pugilists apart.

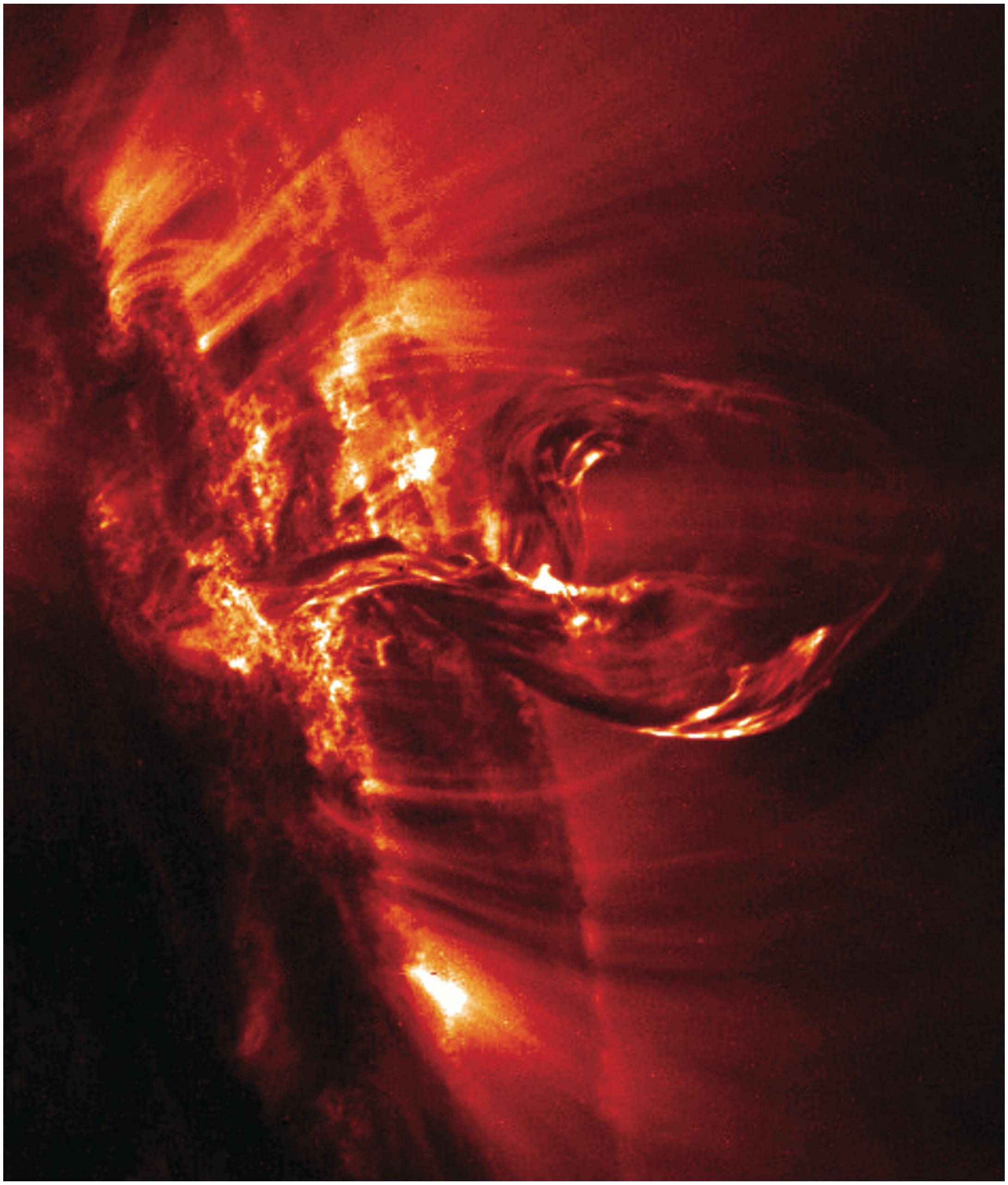
When the attempt fails and the two oppositely-charged regions come in contact, the disruption and reconnection of the magnetic lines of force that had suspended and nourished the great mass of chromospheric plasma are suddenly unleashed, with the same force and some of the same effects as an explosive solar flare. When this happens, the filament can be torn loose from its magnetic roots at the solar surface and flung outward, bodily, from the Sun.

A rising solar filament, driven upward and outward at speeds of several hundred to a thousand miles per second is but one manifestation of a more extensive magnetic disturbance in the corona which expels much larger loops of coronal plasma at far greater speeds. In the course of these larger-scale magnetic reconfigurations, entire streamers can be torn from the corona and thrown outward into space, like petals pulled from a daisy. These immense coronal mass ejections (or CMEs) expand as they proceed outward from the Sun, and soon exceed by far the size of the star that gave them birth and sent them on their way.

Filaments or prominences are common features on the Sun at times of increased solar activity. Those known as active prominences, which straddle a region of magnetic activity with feet in regions of opposite magnetic polarity, can erupt within a few days of their formation. Another class, found in quieter and less rowdy places on the surface of the Sun, can literally hang around for months at a time, peacefully and with little change, until they slowly fade away.

They can also grow into immense structures that seem wholly out of scale when compared with anything else on the surface of the Sun: truly gargantuan features when we see them extended outward above the limb. Or on the disk, where as dark filaments they look a lot like segments of the Great Wall that snakes its way across the northern hills of China.

The largest of all are the long-lived and relatively inactive quiescent prominences that can tower tens of thousands of miles above the surface of the Sun, and extend for hundreds of thousands of miles. Were one of these large quiescent prominences somehow suspended in the space between the Earth and the Moon, it would span most of the distance that keeps us apart: a red bridge of many arches in the sky, nearly 200 thousand miles long.



The eruption of a looped solar filament that is rooted in a magnetically-active region near the apparent edge, or limb, of the Sun. The image, from the TRACE spacecraft, was made in the light of the (invisible) extreme ultraviolet spectrum, emitted from regions of the solar atmosphere where temperatures exceed more than two million degrees Fahrenheit.

Coronal Mass Ejections

If sunspot magnetic fields are the gunpowder, flares the muskets and prominences the horse-drawn cannons in the venerable solar armory, coronal mass ejections or CMEs—which came to be recognized but thirty years ago—are truly the heavy artillery. Indeed, interplanetary CMEs are the primary drivers of almost all space weather disruptions, including highly accelerated plasma streams and most major geomagnetic storms, with potential impacts on a wide range of human activities.

CMEs are the product of impulsive changes in the corona, in which entire segments of the outer corona are driven outward from the Sun and ejected into the solar wind stream. They originate in regions of closed magnetic field, most often from the coronal streamers that extend outward from the disk of the Sun like the petals of a flower.

The bulbous, helmet-shaped base of a coronal streamer is formed by closed magnetic fields that are strong enough to contain the coronal plasma at this level and keep it from expanding and escaping as solar wind. This is not the case, however, for the outer extensions of streamers. There the strength of the coronal magnetic field, which decreases with height, can no longer contain the coronal expansion. At this level—between about 0.5 and 1 solar radius above the limb—the coronal plasma is able to stream freely outward from the Sun, producing the typical tapered form of extended coronal streamers.

It is largely the inner parts of a streamer, however, that are expelled from the Sun as CMEs. When the magnetic bindings that contain the base of a coronal streamer are disturbed or catastrophically broken, the plasma that was confined within it—often an entire coronal streamer—is flung outward as from a loaded spring. As it moves outward, the outer edges of the expanding CME often appear as a closed loop, still attached at the Sun, and indeed, few CMEs ever completely sever their magnetic connection to the star.

There is no general agreement as to what initiates the release of a CME, although stressed magnetic fields are undoubtedly involved. One possible explanation holds that when the two foot-points of a large coronal magnetic loop—one rooted in a magnetic region of positive polarity and the other in the opposite sign—are moved relative to each other by the shearing action of differential rotation at the surface of the Sun, the towering loops that form the base of an overlying coronal streamer are directly affected. A likely result is a twisting of the loop that can be relieved only by dynamic realignment and readjustment, with the explosive release of some of its vast store of magnetic energy.

It is also clear that CMEs are a significant player in the evolution of the corona from minimum to maximum levels of solar activity, and that the release of a CME is quite likely a stress reliever that enables the outer solar atmosphere to reconfigure itself in response to underlying changes in the solar magnetic field.

CMEs are expelled from the Sun at a wide range of speeds: the slowest cover a few tens of miles in a second, and the fastest move a hundred times faster. At these speeds slower CMEs will travel a distance equal to the radius of the Sun (430,000 miles) in but a few hours, and the fastest in but a few seconds. It is rare that one can distinguish the movement of anything on the Sun as it happens because the Sun is so far away. But CMEs are so large and fast-moving that through a coronagraph—where most of them are detected and tracked—one can follow the initial outward progress and expansion of many of them in real time.

Coronal streamers that give rise to CMEs often become more luminous a day or so before the eruption, as though signaling their own impending demise. And in time, moreover, a replacement streamer may re-form in the vacant space where the original was torn away. What has happened, in any case, is a violent restructuring of a large part of the solar corona, an expulsion of a piece of it which expands like a balloon as it moves outward, and the release of a large amount of energy into interplanetary space.

Carried off with the expanding plasma cloud is the embedded magnetic field that gave it form and structure. Any prominence that lies within the bulbous base of the same streamer is also often torn away. These are commonly uprooted and carried away from the Sun with the CME, initially as a cooler and denser arch of chromospheric material enclosed within the expanding coronal loop, though driven outward at a somewhat slower speed.

Often solar flares are also seen in the same active region on the Sun, at about the same time or shortly after the eruption of a CME. But the flares and eruptive prominences that are so often associated with coronal mass ejections do not necessarily provoke the CME, or the other way around. They are, rather, different consequences of the same large-scale, magnetic event.

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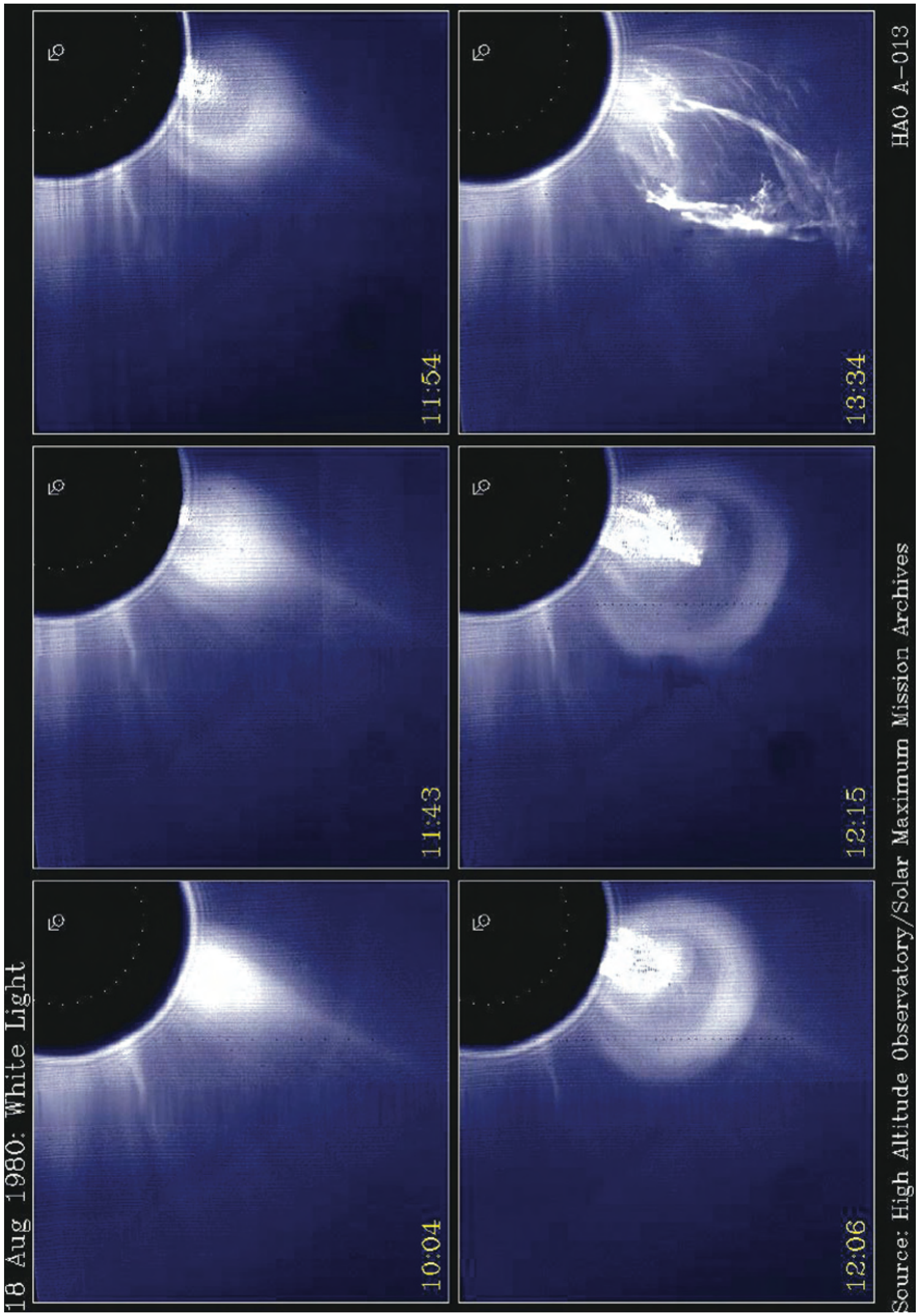
Although some move faster, the average speed of a CME through the outer corona—about 250 miles per second—is still far short of the velocity needed in the corona to overcome the immense restraining pull of solar gravity. Yet they escape. This and the fact that none of them fall back to the solar surface—in the manner of arrows shot into the air—tell us that other forces within the corona continue to accelerate a CME, once launched, to send it ever faster on its way.

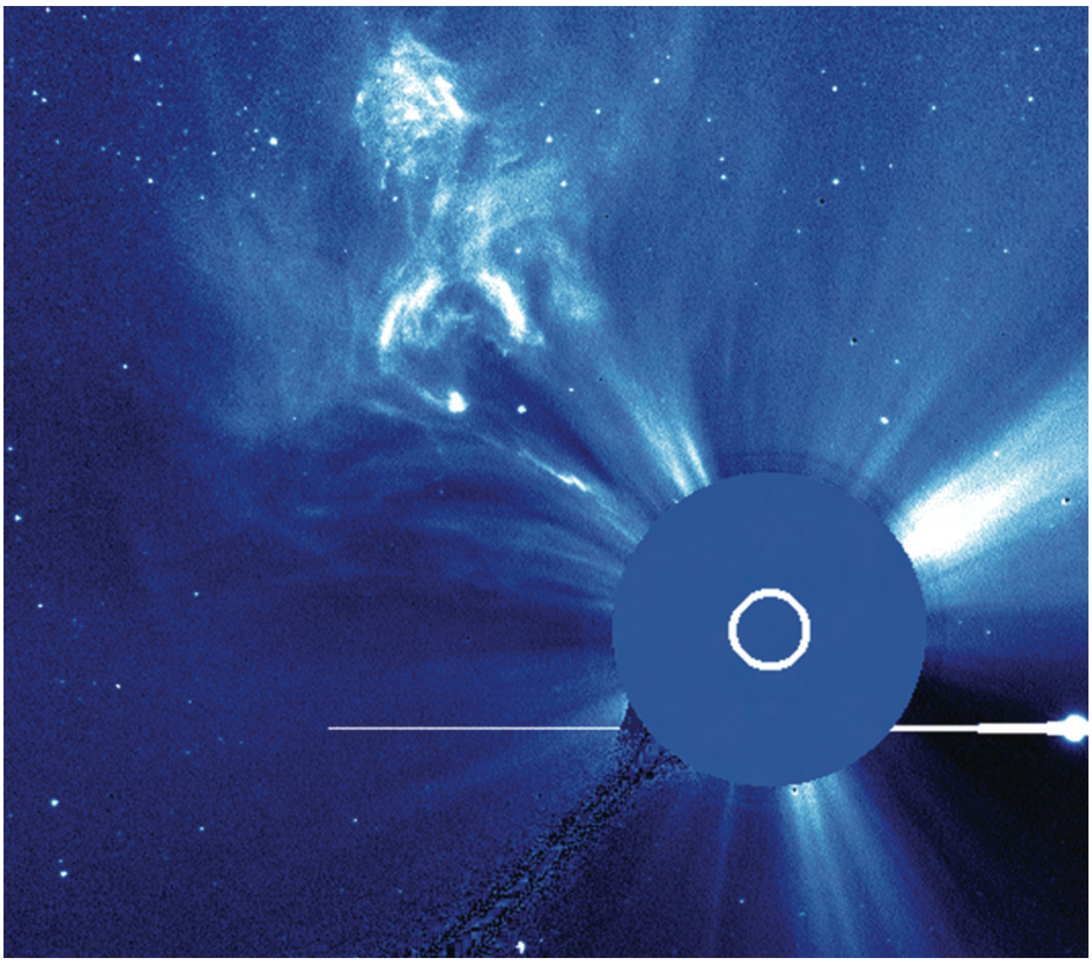
CMEs could be compared to tornadoes, hurricanes and tsunamis on the Earth were these coronal expulsions less frequent and commonplace. As noted earlier,



The formation and release of a mass ejection (CME) in August of 1980, near the maximum of solar cycle #21, showing its destructive impact on the coronal streamer of which it was a part. The sequence of six images (arranged from bottom left to top left, then bottom right to top right, cover a period of 3½ hours, with most of the major changes in the half hour captured in images 2, 3, 4 and 5, which are each about ten minutes apart. The loop-like CME seen in the last image, with a mass of about ten million tons, will speed outward from the Sun into interplanetary space at a million miles per hour or more. CME's were not discovered until the early 1970s, when solar coronagraphs capable of seeing them were put into space.

how often they occur generally follows the phase of the 11-year sunspot cycle. On average there are between three and four CMEs per day when the Sun is near the peak of its activity cycle. At times of minimum activity, the number falls to about one every ten days. Thus, when averaged over the entire cycle, the Sun produces on average of about one per day, like a hen laying (very large) eggs.

In the process of this continuing celestial workout, the Sun sheds a lot of pounds, whether reckoned per month, per week, or per day; and unlike us, none of the lost weight will ever be regained. A typical CME carries off a thousand million, i.e., a billion tons of coronal plasma. In one month, at the average rate of one CME per day, the Sun loses an amount of mass equivalent to the weight of all the water in the five Great Lakes, one of which is the largest fresh water lake in the world.



The expulsion of a CME from the Sun, made up of an entire coronal streamer and the chromospheric prominence that lay within it. The diffuse remains of the streamer (at about 11 o'clock) is, like the rest of the white-light corona, composed of solar electrons illuminated by sunlight from the here-hidden photosphere. The ejected prominence that trails behind and slightly to the left of the coronal mass retains its original looped shape, though now in greatly expanded form. The size of the solar disk, dwarfed by what it has sent into space, is shown as a white circle in the center of the larger circular region of the inner corona that is blocked by the coronagraph.

But the corona isn't made of water, and the Sun is not the Earth but an object that is 330 thousand times more massive. Had the Sun sent out not one but a hundred CMEs each day since it first became a star, 4.6 billion years ago, its total mass would by now have been reduced by about .01%: a fractional change which for a 210 lb. dieter would correspond to a total weight loss (after all this time and all that effort!!) of less than a third of an ounce.

PRINCIPAL MANIFESTATIONS OF SOLAR ACTIVITY

FEATURE	DESCRIPTION	LIFETIME	EFFECT ON THE EARTH
Sunspots	Dark spots that appear on the white-light disk of the Sun, each the locus of strong and concentrated magnetic flux	Days to a month or more	Incremental reduction in the total solar radiation received at the Earth
Plages	Bright patches in the photosphere and chromosphere, most often in association with sunspots	Days to a month or more	Incremental increase in the total solar radiation received at the Earth
Flares	Sudden, explosive brightenings in magnetically-active regions in the chromosphere and corona, accompanied by the release of highly energetic electromagnetic radiation and atomic particles	A few minutes to an hour or more	Drastic, transitory increase in the flux of x-ray and extreme-ultraviolet radiation with effects on the upper atmosphere; release of highly energetic protons, posing hazards to manned and unmanned spacecraft and jet aircraft at high latitudes
CMEs	Expulsions of large segments of the outer corona, often becoming larger than the Sun itself, into inter-planetary space	Days to weeks	Acceleration of atomic particles in the solar wind, with concomitant impacts on the magnetosphere and upper atmosphere