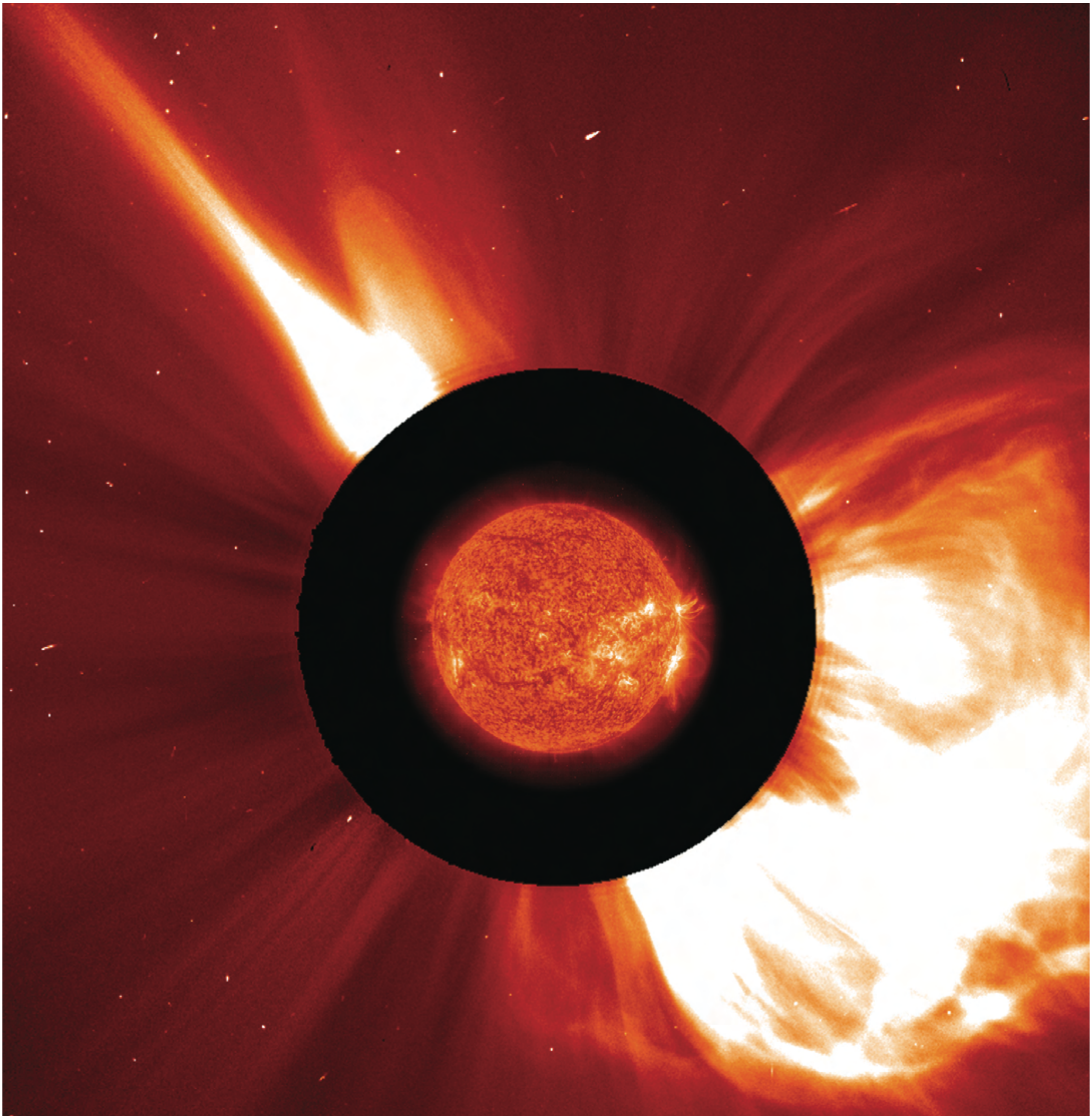

The birth of a coronal mass ejection, July 2005. The rapidly expanding blob, lower right, of what was once a well-formed coronal streamer (like that at upper left) is propelled outward, faster than a speeding bullet, into the heliosphere. This image of the Sun's outer corona was made in white-light by a continuously-operating coronagraph on the SOHO spacecraft. The inner image of the chromosphere, which identifies the relevant magnetically-active regions on the underlying surface of the Sun, was made at the same time and on the same spacecraft in the far ultraviolet. It has here been overlaid, to scale and properly oriented, on the black occulting disk of the corona, which blocks the solar disk and inner corona from our view. Violent CMEs of this kind are quite separate from the far gentler outward flow of less energetic particles that pour continuously outward from all parts of the Sun in the solar wind.

VARIATION IN THE FLOW OF PARTICLES AT THE EARTH

The Nature of Arriving Particles

Each atomic particle that leaves the Sun—in the solar wind, in CMEs, or from solar flares—is a small piece of the star itself, taken chiefly from the corona and transition zone. Because of the extremely high temperatures in these source regions, the atoms that escape the Sun have lost most or all of their electrons, yielding positively-charged ions and negatively charged electrons. For hydrogen—which is far and away the most abundant element on the Sun—the products of ionization are simply protons and freed electrons. For helium, the next abundant, and for all the other elements the products are free electrons and ions of different positive charges.

These newly-released particles, since they carry an electric charge, are at once bound to the strong magnetic lines of force that thread the solar atmosphere. Particles that leave the Sun in the solar wind carry these embedded magnetic fields with them: like missionaries sent on their way with bibles in hand. An assemblage of charged particles of this sort describe a state of matter—called plasma (a gas composed of ionized or charged particles)—whose behavior is quite different from that of the more familiar gaseous, solid, and liquid states of matter. One of these differences is the capability of retaining an imbedded or "frozen in" magnetic field.

The combination of charge and embedded field in solar plasma very much affects what happens when the ejected plasma comes in contact with the magnetic fields of the Earth or other planets.

Depending upon their energies, solar particles that arrive at the Earth produce quite different impacts. The least energetic are the solar wind plasmas, in either slow- or high-speed streams, as well as most particles carried Earthward in CMEs, which in either case consist of weaker, thermal electrons and ions. Their energies per particle (expressed in electron-volts, or eV) tell of the temperature in their region of origin in the chromosphere, transition zone, and corona of the Sun, and range from a few eV for electrons to at most at few keV ("kilo" or 1000 electron volts) for protons and other ions.

Highly accelerated (or suprathermal) particles include protons and other ions expelled more impulsively from flares and more commonly, particles in the

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solar wind plasma that have been accelerated en route to the Earth by fast-moving CMEs. The energies of flare particles are commonly in the range of MeV (millions of electron volts).

It is the considerable energy of these accelerated, suprathermal particles that produces significant terrestrial impacts and effects. These effects include, among others, splitting atoms and molecules apart in our upper atmosphere; creating and sustaining the Earth's ionosphere; and imposing direct hazards to human passengers in either air or spacecraft.

Galactic cosmic ray particles are more energetic, with typical particle energies in the GeV ("giga" or 10^9 electron volts) range, although their range of energies spans twelve orders of magnitude. Some of these incoming alien particles are endowed with energies so awesome—up to 10^{20}, or a hundred billion billion, electron volts per particle—that for most practical purposes they are unstoppable.

The speed of solar particles—a function of their mass and kinetic energy and in the case of the solar wind, the bulk motion of the plasma—also covers a wide range. A solar wind electron with an energy of 10 eV travels at a characteristic speed of about 1000 miles per second, to arrive at the Earth in a little less than a week. An energetic proton from a solar flare with an energy of 10^9 eV will travel a thousand times faster—at half the speed of light—covering the same vast distance in but 15 minutes. And because the proton is so much heavier, its potential impact on the Earth is immensely greater.

A stream of solar protons with energies in the range of 10^9 eV and moving at this near-relativistic speed constitutes a potentially fatal threat to anyone outside the atmosphere who should happen to cross its path, and as noted earlier, an almost unavoidable one, for they can penetrate four inches of lead.

ENERGIES AND CORRESPONDING TEMPERATURES OF SOLAR ATOMIC PARTICLES

PARTICLE ENERGY IN ELECTRON VOLTS	CORRESPONDING TEMPERATURE (°F)	TYPICAL SOURCE REGION
0.5	10,000	Solar photosphere
1	20,000	Low chromosphere
10	200,000	Transition zone
100 eV to 1 keV	10^6 to 10^7	Corona
MeV to GeV	10^{18} to 10^{13}	Solar flares

Solar Sources

Energetic atomic particles from the Sun begin their outward journeys from a variety of starting points in the solar atmosphere: some from eruptive prominences and active regions; some from coronal holes; and others from long coronal streamers. Some leave from low latitude regions on the Sun and others from its poles. But in every case their point of origin and direction of flow are defined by local characteristics in the Sun's magnetic field.

The most energetic streams of particles that reach the Earth arrive from either explosive solar flares or more often, from shock waves created by fast CMEs in the solar wind plasma. The energy that initiates and propels particles outward from flares comes from the sudden conversion of some of the magnetic energy in solar active regions into thermal and kinetic form. These short-term, impulsive blasts of highly energetic particles are superposed on top of slower and less energetic solar wind plasma.

What we sense at the Earth is a slowly-changing background of galactic cosmic rays on which fast and slow streams of solar wind plasma are superposed. On top of these are more sporadic episodes of higher energy particles that result from solar flares and CMEs.

SOLAR PLASMA AND ENERGETIC PARTICLES THAT IMPINGE UPON THE EARTH

SOURCE	ORIGIN	TYPES OF PARTICLES
Solar Wind	Open field regions in the corona	Mostly protons and electrons
CMES	Closed field regions in the solar corona	Protons, electrons and ions
Solar Flares	Solar corona and chromosphere	Protons, electrons and ions
Galactic Cosmic Rays	Supernovae, neutron stars and other galactic and extragalactic sources	Mostly protons, some ions and electrons

Particles Borne Outward in CMEs

Ejections of mass from the corona, called CMEs, are triggered by sudden realignments and reconnections in the magnetic fields that give form to this ethereal outer extension of the Sun. In the course of these violent events a long coronal streamer of the sort that extend outward for millions of miles from the surface of the Sun can be disrupted and rearranged, or wholly torn away. Chromospheric prominences—which are often found within the bulbous base of a coronal streamer and magnetically supported by it—are pulled up and flung outward from the Sun in the same catastrophic disruption.

The expulsion of a CME can often be traced to differences in the rates of solar rotation of adjoining latitude bands on the surface of the Sun. If one foot point of a towering magnetic arch that supports the bulbous base of a coronal streamer moves relative to the other one, it can twist the magnetic structure on which the streamer is built, and sever its moorings to the Sun. The emergence of new magnetic flux in the vicinity of a coronal streamer is another likely trigger of CMEs.

By any measure, the dimensions of a CME are truly immense, and as they move outward they continue to expand.

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The expulsion of a CME from the Sun might correspond on Earth to suddenly pulling up an entire forest of giant sequoias by their roots, and flinging them outward like a handful of weeds into space. Or perhaps the sudden volcanic obliteration of an entire island—as indeed happened off the tip of Sumatra one summer day in 1883.

But neither simile is apt, for in the corona the disturbance is of continental scale and often results in the violent obliteration of a sizeable piece of the entire outer corona. What we chance to see from the Earth in these minutes of unbridled solar rage are gigantic blobs of plasma, larger than the Sun itself, hurled outward from the star at velocities of up to 1000 miles per second: an almost unimaginable speed for so large an object, and fast enough to carry it from LAX to JFK in but three seconds' time. When the direction of an expelled CME carries it toward the Earth, we can expect it to reach the outer boundary of our magnetosphere in typically three to four days, although the fastest get here in but 19 hours.

CMEs are expanding pieces of solar plasma containing protons, electrons, and ions of different elements that are loosely bound together by the embedded magnetic field that they have taken with them from the Sun. As noted earlier, CME plasma is not particularly energetic, with energies per particle of but a few keV, which are not unlike those encountered in the solar wind. But higher speed CMEs can instigate shock waves in the solar wind through which they pass, accelerating ambient wind and suprathermal particles to energies measured in MeV. These high-energy, shock-driven particles generally run well ahead of the CME that was responsible for them, and are the principal cause of significant particle impacts at the Earth.

To be fully warned of their impending arrival, we need to have observed the disruption as it happens on the Sun, which is best secured from satellite-borne telescopes and coronagraphs. To tell whether it will strike the Earth we also need to know its initial direction, bulk speed (as distinct from the speeds of individual particles) and projected course. To forecast the likely consequences at the Earth we need to know more about the CME, including its likely impact on the slower-moving solar wind ahead of it and the polarity (north pointing or south pointing) of the magnetic field in the approaching plasma.

Particles From Solar Flares

Explosive solar flares also release streams of highly energetic particles outward toward the planets and into the heliosphere, although they are not the source of the largest impacts at the Earth.

Like CMEs, solar flares represent the instantaneous conversion and release of some of the magnetic energy contained in highly localized and magnetically unstable regions on the Sun, and from the acceleration of these charged particles in their passage through the outer solar atmosphere. Unlike CMEs, however, much of the truly immense magnetic energy that is converted in a flare is released as a short and intense burst of x-ray and EUV radiation.

Were our eyes able to see the disk of the Sun in the EUV and x-ray portion of the solar spectrum we would need no telescope to tell us when and where on the Sun a major flare occurred, which is not the case for visible radiation. As noted earlier, for a few minutes at the start of a solar flare the localized brightening in that one small area—seen in the light of x-ray and EUV radiation—would appear so intense that it would far surpass the brightness of all the rest of the solar disk.

Most of the atomic particles that are thrown off from a flare are electrons that were separated from atoms of hydrogen, helium, iron and other chemical elements in the hot chromosphere and corona. With them, though fewer in number, are the ions that remained when the electrons were freed.

Of all flare particles, solar energetic protons (or *SEPs*) pose the greatest hazard to both life and equipment in space, due to the combination of their mass and speed. The fastest stream outward from the star at half the speed of light, with energies per particle of tens of billions of electron volts. At these near-relativistic speeds they can travel the 93 million miles to the Earth in about fifteen minutes—about the time it might take us to eat breakfast.

Once within the Earth's atmosphere, SEPs will spend most of their prodigious energy in repeated collisions with atoms and molecules of air. But before that happens they can pierce almost any metallic shield.

Manned space flights are particularly at risk, and especially those missions that venture beyond the denser atmosphere and the bounds of the magnetosphere, whether on a short trip to the Moon or a much longer journey to Mars, and whether the crew is inside or outside the spacecraft. Nor would places of apparent shade on the surface of these distant landing sites offer certain protection, because the Sun throws curve balls.

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Upon leaving it, charged particles closely follow extended magnetic field lines that are curved into spiral form by solar rotation. At the Moon's distance from the Sun (the same as that of the Earth) the angle of arrival is tilted about 45° from the line of sight to the Sun, and on more distant Mars, about 55°. Moreover, because of the way incoming charged particles are deflected or "scattered" in all directions by the intervening medium, on the Moon or Mars as elsewhere in space there are as many solar particles arriving from the anti-solar direction as from the opposite, Sun-facing direction.

Given these circumstances, finding shelter may not be easy. Moreover, to take full advantage of the few available minutes of warning time, observers on the Earth must have witnessed the initial burst of the flare, recognized its severity and reacted quickly to sound the alarm.

The best hopes for extending the warning time for these major solar events are through more accurate predictions, issued as far in advance as possible, of when and where on the Sun a CME or major flare is likely to occur; or to avoid all manned spaceflight beyond the magnetosphere during the five or six years of maximum activity in the 11-year solar activity cycle, which is when the most CMEs and largest flares are most likely to occur.

Galactic cosmic rays are a horse of a different color. While there is hope of minimizing the effects of solar high-energy particle events through a combination of shielding and forewarning, galactic cosmic rays—due to both their extreme energies and omnipresence—present a far more difficult and as yet unsolved problem. In terms of cosmic ray exposure, the opposite option of scheduling long-duration space flights during times of maximum solar activity, when the flux of galactic cosmic rays in the inner heliosphere is significantly reduced, may prove to be the better gamble.

The Solar Wind Plasma

The charged atomic particles that are carried away from the Sun in slow or fast streams of solar wind plasma carry energies per particle of only about one keV. But they flow outward from the star every minute of every day and through all seasons of the 11-year solar activity cycle, and are often accelerated en route to the Earth.

Protons and other heavy particles in the solar wind can be accelerated by faster moving CMEs to energies that can exceed those in flare-produced solar energetic protons. Moreover, the threat of these CME-accelerated particles to space travelers or space equipment is greater than that from solar flares, since they last so much longer. Exposure to particles from flares extends typically from a few minutes to half an hour, while an accelerated stream of solar wind plasma can continue for a matter of days.

Particles in the solar wind plasma come from wherever there are open field lines in the Sun's corona: from the poles, the equator, and places in between, and in so doing spray outward from the Sun in virtually all directions.

Many that leave the polar regions of the Sun are channeled by magnetic lines of force that curve gracefully outward from the Sun toward lower solar latitudes. Many of these and all that come from more equatorial latitudes will continue outward into space on fixed, straight-line courses that take them into the realm of the planets. As they proceed outward, the speeding plasma streams—initially more compact—gradually expand into an ever-wider cone: like pellets from the muzzle of a shotgun.

Eventually, they will fill every part of the immense heliosphere. But in the first leg of their long outward race—as they pass the milestones that mark the orbits of first Mercury, then Venus, Earth, Mars, and the more remote planets—the individual streams remain largely separate and distinct: in spite of the pushing and shoving that happens when they are overtaken by faster moving particles in CMEs.

Only a miniscule fraction of what the Sun releases in the solar wind will encounter the Earth or other planets, all of which are all small targets at great distances. Seen from the Sun, the Earth would appear about as large as a ping pong ball held up at the far end of a football field: more like a star than a planet, and though perhaps as bright, only half as large as the planet Jupiter appears to us.

Characteristics of Slow Solar Wind Streams

Slow-speed streams of solar wind plasma, made up of predominantly protons and electrons and a much smaller number of heavier ions, move outward at about 200 miles per second. On average they will arrive at the orbit of the Earth in four to five days, and at Mars in about a week. As in faster solar wind streams, the energies of individual electrons fall in the range of one to twenty electron volts and for protons about 700 eV (0.7 keV) per particle. Apart from this is the energy in the bulk motion of the slow-speed solar wind plasma, which is derived from the average of individual particles.

The initial trajectory followed by slow-speed plasma is determined by the shape and placement of individual streamers. Solar plasma coming from streamers in or directed toward higher latitudes will expand outward in a direction that is tilted upward from the plane of the Earth and other planets. The flow of particles from a streamer whose base lies at lower solar latitudes, on or near the Sun's equator, will be roughly parallel to this plane. Since streamers are found at low latitudes in all seasons of the 11-year solar cycle, the Earth is continually bathed in the slow-speed solar wind, and less commonly in gusts of the high-speed wind.

High-Speed Solar Wind Streams

High-speed streams of plasma in the solar wind race outward from low in the corona at speeds of 350 to 550 miles per second that clearly distinguish them from those in the slower wind. Both high- and low-speed streams of plasma are present in the space that separates the Earth from the Sun, although they cannot interpenetrate, for they follow magnetic field lines from different regions on the Sun. As emphasized earlier, either slow or fast solar wind streams can be disturbed by suprathermal particles which are carried outward from the Sun in either flares or in CMEs. These can produce shock waves in the ambient wind through which they pass, greatly accelerating some of the plasma.

At these higher velocities the high-speed solar wind plasma arrives at the orbit of the Earth within 2 to 3 days and at Mars in 3 to 4. Energies per particle are also somewhat greater: typically ten to thirty electron volts per particle as opposed to a slow-speed average of about 10 eV. The bulk-flow properties of the high-speed wind, though quite different for protons and electrons, are in this case comparable to the thermal energies of the particles within it.

As noted earlier, high-speed streams can be traced to regions on the Sun—called coronal holes—where the density is much lower than in the surrounding corona and where there are no concentrated magnetic fields or coronal streamers. These regions of open magnetic field lines offer a direct path for the escape of high-speed solar wind plasma.

The coronal holes that persist the longest are found at the two poles of the Sun, where they are present in all but the most active years of the solar cycle. Other large coronal holes also appear in middle and lower latitudes on the Sun when it is less active, separating large magnetically-active regions on the disk. The result is a strong solar cycle effect in the solar latitudes where coronal holes appear, and in the number of expected high-speed streams in the solar wind.

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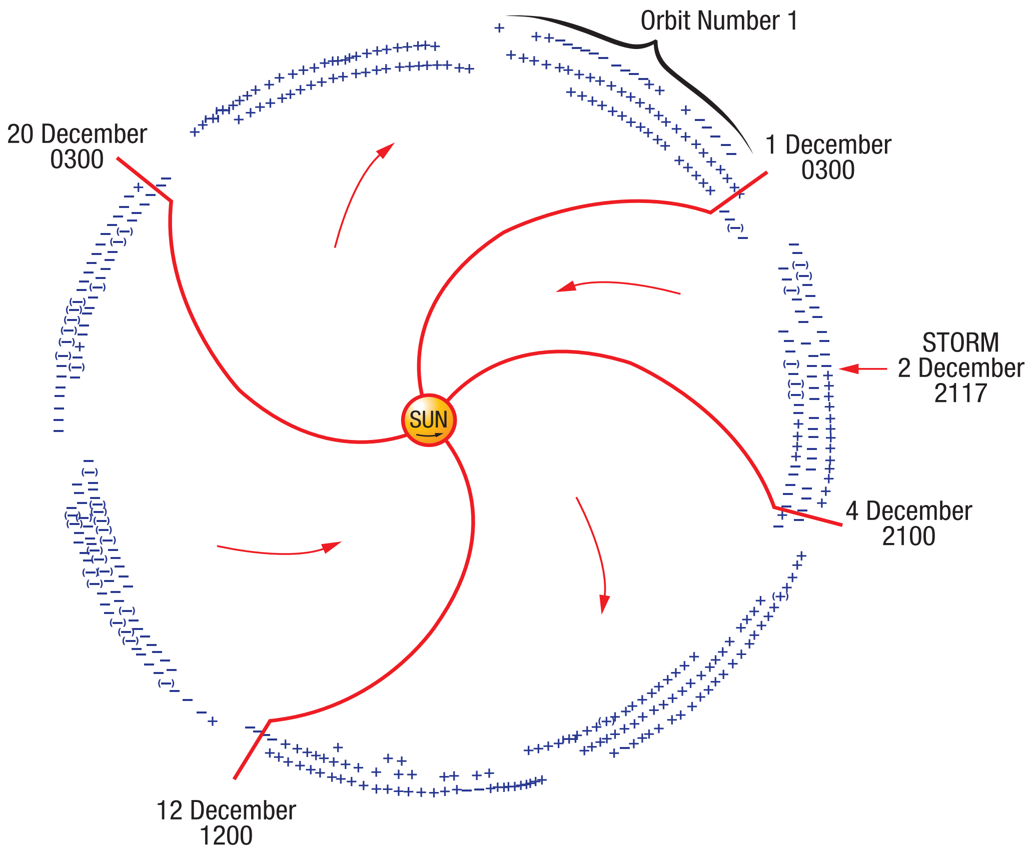
When the Sun is totally eclipsed and its poles are sufficiently clear of high-latitude coronal streamers—as in years of minimum activity—we can actually see the high-speed streams of plasma that flow radially outward from the poles. They appear as a crown of slender white coronal plumes, made visible to us by the same process that illuminates all the rest of the corona: namely, the scattering or redirection of white light from the photosphere by coronal electrons.

Sectors in the Sun's Extended Magnetic Field

The open magnetic field lines that are carried in the solar wind plasma are drawn outward from the star like trailing ribbons with one end still attached to the Sun. Plasma streams move outward from the Sun along radial lines. But because they are tethered to the star, the magnetic field lines that trail behind them are wound around the Sun in loose spirals by solar rotation, like the spiral arms of a rotating galaxy.

The magnetic signature carried outward in each expanding stream is impressed upon it at its place of origin on the Sun. As a result, the magnetic properties of the expanding solar wind at low latitudes are divided into discrete segments of common polarity called sectors. Some have originated in regions of predominantly "outward pointing" polarity on the Sun, and others in places of predominantly "inward pointing."

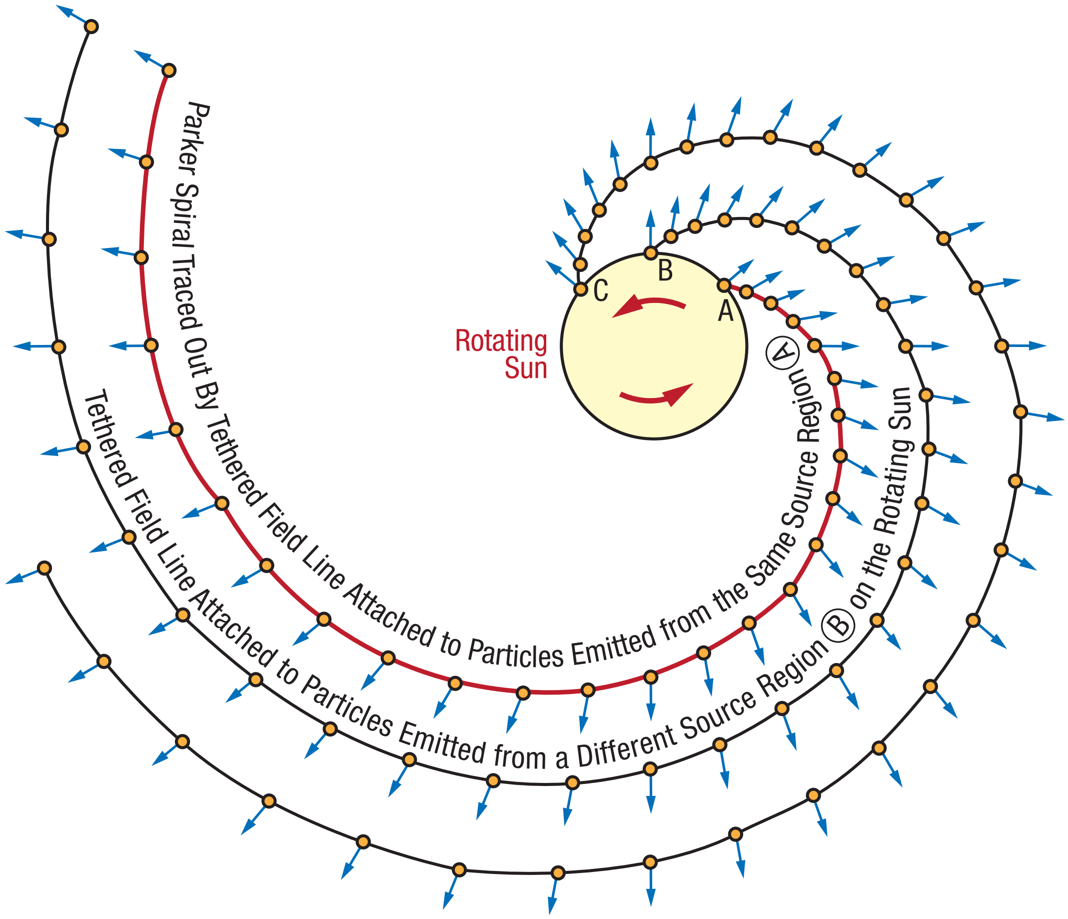
Since these sources are commonly traced to adjoining regions of opposite magnetic polarity, the solar wind streams emanating from them expand outward in adjoining, oppositely polarized sectors. As these curved sectors, fixed at the Sun and rotating with it, sweep by the Earth—like the sprays from a revolving lawn sprinkler—the polarity of the interplanetary magnetic field sensed at the Earth will switch from one polarity to the other each time a sector boundary sweeps by.



A schematic representation of the Sun, rotating counterclockwise as seen from above its north rotational pole, and the magnetic characteristics of the solar wind that flows outward from it. Particles coming from extended regions of prevailing positive or negative magnetic polarity on its surface carry the local dominant polarity with them, forming magnetic sectors of like sign, four of which are shown in this example. This causes the magnetic polarity of the wind received at the orbit of the Earth to switch from prevailing positive (indicated here from actual dated measurement by blue + signs with red outward directed arrows and blue negative -, with red inward directed arrows) as the boundaries of the sectors are swept by the Sun's rotation past the Earth. The curved form of the sectors and of the tethered magnetic field lines carried within them results from the combination of solar rotation and the radial outward flow of the solar wind.

By the time the solar wind plasma reaches the orbit of Venus—about ¾ as far from the Sun as we—the rotation-induced curvature in the sectors has turned the direction of their original magnetic polarity through about 30°. Farther on, at the orbit of the Earth the angle is more nearly 45°.

Although the plasma particles are carried radially outward from the Sun, the location from which they came is carried by solar rotation east-to-west (left to right) across the face of the Sun during the time of their outward travel. Due to this effect, streams of plasma emitted from solar features that are near the apparent central meridian of the solar disk will curve away from the Sun-Earth line as they move outward, and will ultimately miss the Earth. It is not until the rotation of the Sun has carried an active region several days westward—to an



The curving magnetic field lines, tethered at the rotating solar surface, which are carried outward in the solar wind from three source regions (A, B, or C in this schematic drawing), generate the abiding heliacal form of the Sun's extended magnetic field. Blue arrows indicate the always-radial direction of the wind front as it progressed outward.

apparent solar longitude of about 45° west—that it is in a position from which plasma expelled from it is most likely to strike our planet.

Pushing and Shoving on the Way to the Earth

Outward moving plasma in fast- and slow-speed solar wind streams can interact mutually, slowing the fast wind and speeding up the slow. But as noted earlier the more telling disruptions on their way to the Earth occur when these plasma streams in the solar wind are overtaken by more energetic particles from CMEs and less often, from solar flares.

In these cases the CME or flare particles, which move much faster than the overtaken plasma, produce transient disturbances in the solar wind that, in turn, can provoke large geomagnetic storms on the Earth, with impacts on life and society.

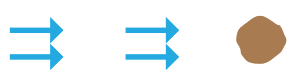
A typical disturbance of this kind will abruptly raise the bulk flow speed in the solar wind plasma from perhaps 200 to 600 or more miles per second. This produces a region of high pressure on the leading edge of the disturbance that is bounded by a forward-moving shock wave that compresses and heats the solar wind plasma. Shock-acceleration in the solar wind plasma produces flows of very high energy particles which are responsible for the longest-duration and terrestrially most significant SEP events.

When Solar Particles Strike the Earth

Streams of solar wind plasma that come upon the Earth are initially deflected by pressure forces at the magnetospheric bow shock and soon after, at the magnetosphere itself. Nevertheless, a number of these fleeing particles from the Sun—depending on the magnetic polarity and energy of the incoming plasma, its speed, and where it comes in contact with the magnetosphere—will still find their way through or around these barriers.

The passing hordes that are wholly deflected around the Earth still leave their mark on the planet by distorting and distending the shape of the magnetosphere, which ultimately affects conditions at the surface of the Earth.

To streams of approaching plasma, the Earth's magnetosphere presents an obstacle much like a protruding stone in the middle of a tumbling mountain stream.



When solar wind plasma moving at supersonic speed encounters an obstacle like the planet Earth it develops ahead of its path a dense and abrupt compression called a shock wave through which the solar plasma must pass. The same is true in a more familiar instance, when the object is moving and the fluid is fixed, as when—accompanied by an audible sonic boom—an accelerating jet aircraft exceeds the speed of sound.

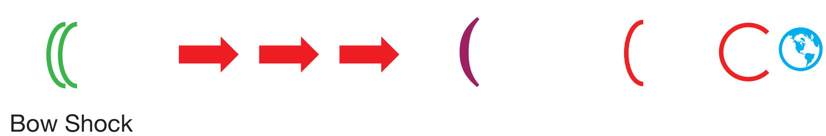
In the case of the solar wind and the Earth, the obstacle is not the solid planet itself, but the lines of force of its magnetosphere. To streams of charged atomic particles moving at supersonic speeds these present an equally disturbing obstacle, since the two magnetic fields—one from the Sun, the other at the Earth—cannot interpenetrate.

The shock wave produced at this encounter is called the bow shock of the magnetosphere, due to its similarity to the bow wave that forms in the water ahead of the bow a moving ship. In the nautical case, the wave is formed not where the sharp edge of the bow slices the water but some distance ahead of it.

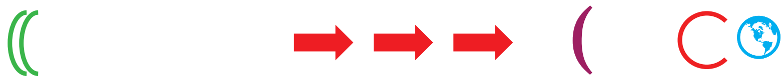
In the same way, the bow shock in the solar wind is created well ahead of the outer boundary of the magnetosphere and at a great distance from the Earth itself. Depending upon the speed and energy of the approaching solar wind, the bow shock is met typically 50,000 miles ahead of the Sun-facing side of the Earth, and sometimes as far as 80,000 miles, or as much as a third of the distance to the Moon.

In passing through the curved bow shock—a zone of turbulence often less than 100 miles thick—the onrushing solar plasma is heated, slowed to sonic speeds and deflected.

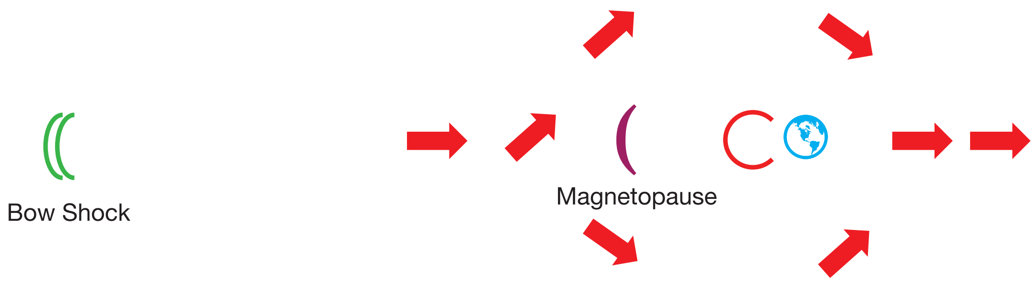
The next obstacle it will encounter is the magnetopause, the shell or outer boundary of the Earth's magnetic field, which lies roughly half-way between the bow shock and the solid Earth. Even there, the streaming plasma still has about 40,000 miles yet to go to reach the planet itself.



As it approaches this second barricade, the onrushing plasma compresses the curved lines of force that connect the two magnetic poles of the planet, flattening the shape of the Sun-facing side of the magnetosphere and pushing the magnetopause closer to the surface of the planet it protects.



Because the Earth's magnetic field is so much stronger than that carried in the oncoming solar plasma, it repels the brunt of the surge. Under normal conditions the deflected solar plasma is channeled around the magnetopause to continue its course, like a diverted stream, on beyond the Earth.

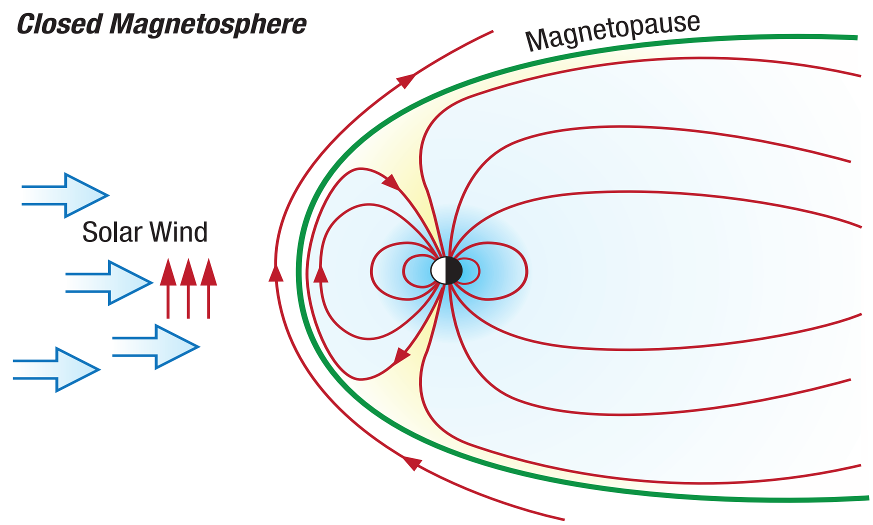


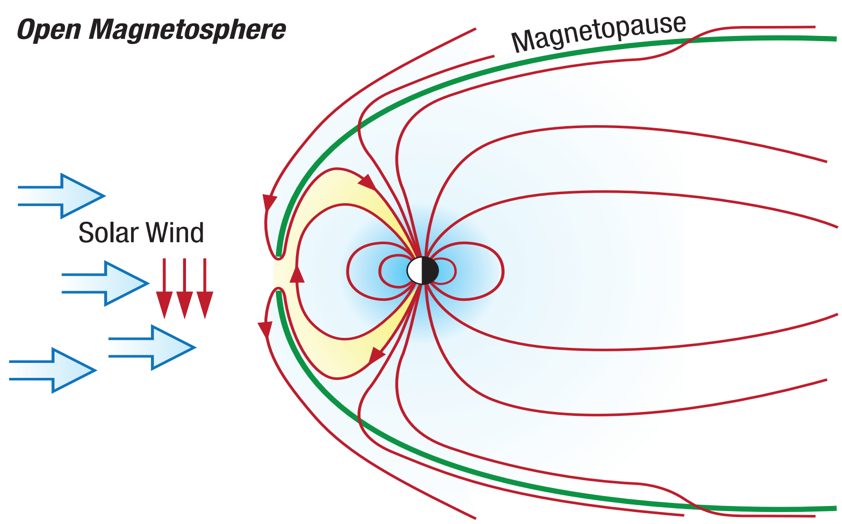
Through the Guarded Gates

However, should the magnetic polarity in the stream of incoming solar particles be oriented such that a significant component is directed opposite to that of the Earth—that is, south-pointing instead of north-pointing—the transported solar field and that of the Earth can directly connect to each other. This process of magnetic reconnection on the day-side of the magnetosphere opens the normally closed magnetopause, allowing the direct entry of charged particles from the Sun into the Earth's magnetosphere and on down into the thermosphere.

The reconnection process creates open field lines, rooted at one end near the poles of the Earth, that thread the magnetosphere, affording paths of access for the newly admitted particles. In so doing, they temporarily expand the diameter of the polar cusps, enlarging the funnel-shaped openings at the Earth's magnetic poles, thereby increasing the area through which diverted solar plasma moving through the magnetosheath can flow into the magnetosphere.

The momentum of the solar wind drags the open field lines rooted at the two poles of the Earth downwind into a long cylindrical magnetotail, made up of a north lobe and a south lobe, each D-shaped in cross section, and stacked back-to-back ⊖. Since the field lines in one originate at the north magnetic pole of the Earth and the other at the south, the lobes have opposite magnetic polarity, and are separated like a sub sandwich by a thin slice of hot plasma and weak magnetic field called a plasma sheet.





Upper right: Lines of force of the Earth's magnetic field, portraying with arrows their presently-fixed, north-pointing direction of polarization. Field lines emanating from either magnetic pole connect with the opposite pole, defining a closed magnetic field, as shown here. The field lines streaming out to the right, "downwind" side in this figure are also closed, connecting with lines from the opposite pole but at a distant point well beyond the limited portion of the Earth's field shown here. At upper left: the approaching solar wind that flattens the Earth's field on the Sun-facing side. In this case it carries the imprint of a similarly north-pointing magnetic field (red arrows) from the Sun's surface. Since it is parallel to that of the Earth no Sun-Earth connection is made.

Lower left: An approaching solar wind or other disturbances such as a CME that carries instead a south-pointing magnetic signature. Lower right: the effect of this oppositely-directed field on the Earth's magnetosphere. Within a limited point near the Earth's equator on its Sun-facing side, the direction of the solar field is exactly opposite to that of the Earth, allowing a direct electric connection between the two, through a process called magnetic reconnection. For a short time, this opens a gateway for the transfer of charged particles from the Sun directly into the magnetosophere, where within the yellow region, they follow terrestrial field lines into the upper atmosphere of the planet to produce a magnetic storm with accompanying aurorae and potentially major disruptions at the Earth's surface.

In the distant magnetotail, stretched-out field lines attached to the Earth's north magnetic pole are pinched by the force of the streaming plasma into contact with those of the opposite magnetic polarity rooted in the south magnetic pole. In these regions of contact—called neutral lines—solar plasma that has streamed outward in the magnetosheath is able to enter the outer magnetosphere and become entrapped. Once there it is channeled all the way back to the Earth and into the inner magnetosphere and radiation belts.

There is a final means of entry into the magnetosphere, that is also highly restricted: in this case for cosmic and solar particles (as opposed to plasma streams) that are sufficiently energetic to breach the protective magnetopause. When this happens these highly energetic particles make their way directly into the upper and middle atmosphere, where they are ultimately stopped by collisions with atoms and molecules of air. To qualify for brute force entry, charged particles must carry very high energies—in the range of about 500 MeV or more—which include both galactic cosmic rays and the most energetic solar particles, such as solar energetic protons (SEPs). How deeply they penetrate into the atmosphere is a function of their energy, their angle of approach and the magnetic latitude at which they enter.

Magnetic Reconnection

As noted above, when the normally-closed magnetopause is for a time opened by magnetic reconnection, it creates a network of open-ended field lines, with one end rooted in the area of the Earth's polar caps. This temporary opening of the magnetopause allows the direct entry of solar particles into the low-latitude, Sun-facing magnetosphere, as well as solar particles that have been deflected around the Earth in the magnetosheath.

Those that enter the magnetopause at the site of magnetic reconnection are directed along the open field lines toward one of the magnetic poles, where some are funneled directly into the upper atmosphere through the polar cusps. Some of the particles traveling around the outer boundary of the magnetosheath also find their way through the polar cusps and into the atmosphere.

Others within the magnetosheath follow newly-opened field lines in the magnetotail, where at one of several possible neutral lines they execute a U-turn to head back in the direction from which they came, toward the Earth and into the inner magnetosphere.

A near-Earth neutral line where this can happen is temporarily established during magnetic reconnection at a distance of about 25 R_E or 100 thousand miles downwind from the planet. A more permanent and more heavily used distant neutral line is located more than 300 thousand miles farther out in the magnetotail, which puts it well beyond the orbit of the Moon.

The opening of the magnetopause during magnetic reconnection events also allows an exchange of particles in the opposite direction: out of the magnetosphere, through the magnetopause and into the magnetosheath where they are returned, unused, back into interplanetary space.

During times of magnetic reconnection the magnetosphere extracts about 2% of the incident energy of the solar wind, of which more than half is returned, unused, to space. But even the small fraction that is retained—stored in the magnetotail in the form of magnetic field energy—can have major impacts. The connection can be maintained for hours or days, and during this time the effects of the direct connection are felt throughout the length and breadth of the entire magnetosphere and in the upper atmosphere of the Earth as well, with significant effects on a range of human activities.

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The orientation of the magnetic field borne in an approaching stream of solar plasma can lie anywhere from opposite to that of the Earth's field to completely parallel to it, or any angle between these two extremes. As previously noted, magnetic reconnection between the approaching solar field and that of the Earth is possible when the fields are oriented oppositely, or more precisely, when a significant component of the vector that describes the orientation of the approaching solar field is exactly opposite to that of the Earth's fixed field.

One of the two simplest cases can be envisioned as the coming together of the shafts of two arrows ↓↑ that are *anti-parallel*, or pointed in exactly opposite directions. Under these conditions, or in the more likely case in which a significant component of the solar field vector is anti-parallel to that of the Earth, a direct connection is possible. But when the orientation of the magnetic field in the incoming plasma stream is the same or largely the same as the portion of the Earth's field with which it comes in contact—i.e., with our schematic arrows pointed in the same direction ↑↑ —a meaningful connection is not possible.

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The present orientation of the Earth's magnetic field is by convention described as "north pointing" in the sense that the direction of magnetic force at the equator is from the south to the north magnetic pole .

And so it has been, with no drastic change in polarity, since the time of the last reversal, when early Stone Age people began to wander into what is now Europe: three-quarters of a million years ago.

When the Earth's magnetic field next reverses direction, from north-pointing to south-pointing , the opposite will apply.

Magnetic reconnection with incoming solar plasma will then take place only when a component of the incoming solar field is oriented in the opposite "north pointing" direction, although the change, once accomplished, will make no difference in the frequency of magnetic reconnection events. Were we here at that time, we would notice not the switch in polarity but a protracted period between states: a period of magnetic confusion when the strength of the Earth's protective field will fall almost but not quite to zero.

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The more-superficial surface magnetic field of the Sun also switches polarity, though at a much faster rate, following a solar magnetic cycle that is twice the length of the 11-year activity cycle. Toward the end of each 11-year cycle the north and south magnetic poles of the Sun switch polarities, from "north pointing" to "south pointing" or vice versa, and remain that way until the end of that cycle and the beginning of the next, when they will switch again, completing one 22-year solar magnetic cycle. Thus the Sun, so often invoked as a symbol of stability and constancy, is the more skittish partner in the Sun-Earth system, having undergone more than 68,000 magnetic reversals since the last time the Earth changed its magnetic mind, about 750,000 years ago.

The magnetic polarity carried in streams of plasma that reach the Earth is determined not simply by the Sun's 22-year magnetic cycle but by the polarity of the local magnetic field in the part of an active region from which the plasma originates, which can be either "north-pointing" or "south-pointing" at any phase of the Sun's 11- or 22-year cycles. Thus the magnetic orientation of the heliospheric magnetic field sensed at the Earth is a continually varying parameter, as a consequence of the presence of discrete regions of opposite polarity on the surface of the Sun and its 27-day rotation.

SOME DISTANCES EXPRESSED IN UNITS OF THE RADIUS OF THE EARTH

FROM THE CENTER OF THE EARTH TO:		DISTANCE IN R_E [≈4000 MILES]
Mean Sea Level	(0 MILES)	1
Peak of Mount Everest	(5.5 MILES)	1.0014
Auroral Displays	(260 – 580 MILES)	1.05-1.08
Near-Earth Orbit		1.10
Geosynchronous Orbit		6.6
Magnetopause in the Direction of the Sun		10
Magnetopause above the N and S Poles		13
Bow Shock at the Nose of the Magnetosphere		15
Nearest Neutral Line in the Magnetotail		25
The Moon at Mean Distance		60
Farthest Neutral Line in the Magnetotail		≈ 100
End of the Magnetotail		> 1000
Venus at Closest Approach		6,400
Mars at Closest Approach		12,200
The SUN		23,500

Effects of Changes in the Earth's Magnetic Field

The degree to which the magnetosphere can deflect incoming solar and cosmic particles depends on its strength, the energies of the incoming particle, and their direction of approach relative to the geometry of the Earth's field lines.

Mercury's magnetic field, for example, is about 100 times weaker than our own. Because of this and the planet's proximity to the Sun—more than twice as close as we—its magnetic field is very highly compressed on the Sun-facing side. As a result, it can hold off the pressure of solar wind plasma no farther than about 1500 miles: a distance above the surface of the planet that is about equal to its radius. This and Mercury's lack of an atmosphere—which allows a direct interaction between its magnetosphere and the solid surface of the planet—permit easier access to incoming energetic particles.

The Earth's field, on the other hand, is sufficiently strong and oriented in such a way that most incoming particles are fended off—at a distance on the Sun-facing side of about 40,000 miles above the solid surface. But it hasn't always been that way, nor will it always be, for the strength and orientation of the Earth's magnetic field is always changing.

The locations of the Earth's north and south magnetic poles wander as time goes by, seldom if ever coinciding with the locations of the two rotational poles. In the Arctic, the peripatetic north magnetic pole is today meandering along near Melville Island in Canada's Northwest Territories, some 800 miles south of the North rotational pole: about the distance that separates Chicago from New Orleans. And it continues to move at a speed of about one mile per day, in response to changes in the internal dipole field of the planet.

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Two corrections need be applied to correct the difference between what a magnetic compass indicates as "north" and "true north" as defined by the direction to the Earth's rotational pole. The first of these corrects for the difference between the positions of the north magnetic and north rotational poles and is called the variation or magnetic declination: a correction that navigators and surveyors routinely apply when using a magnetic compass. (The other, called the deviation, is a local effect that arises from the presence of magnetized metal or ore in the immediate vicinity of the compass itself.)

Since the variation changes from year to year and place to place with the meandering of the poles, the correction for variation indicated on maps, navigational charts and flight maps require frequent updating. Because aircraft commonly employ magnetic compasses, the large Arabic numbers that are painted at each end of airport runways (e.g., 12 to indicate a magnetic heading of 120°, or 30 for 300°) must also be corrected and repainted from time to time.

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A more significant change—in terms of its effect on the efficacy of our magnetic shield—is a well-established long-period variation in the *strength* of the Earth's field.

Five hundred years ago, when wooden ships set sail from ports in the Old World to explore the New, the strength of the magnetic field that kept their compasses pointed north was about 15% stronger than it is today. And stronger still 1300 years before that when, at about the time the Roman Empire reached its greatest extent, the Earth's magnetic field—after a long, three thousand year climb—reached a peak strength that was almost 40% greater than today.

More dramatic than these several-thousand year variations in the strength of the field are longer-spaced reversals in the polarities of the Earth's two magnetic poles: at which time the north and south magnetic poles exchange polarity, though not exactly at the same time.

In the course of these slow and imperfectly synchronized events, the effective strength of the Earth's field—and with it, the protection afforded by our magnetic shield—drops precipitously low, if not to zero, for long periods of time.

Repeated occurrences of magnetic reversals have been identified in paleomagnetic records of the last 80 million years, separated by periods of fixed direction that persist for about 100 thousand to almost one million years. Although the recurrence and timing of these events is highly irregular, the next reversal is widely conceded to be overdue, since the last one occurred in the early Pleistocene epoch, about 750,000 years ago.

Cosmic Rays

The Earth is continually bombarded with charged atomic particles not only from the Sun but from violent events—such as the eruption of a supernova—that happen much farther away, either within our immense galaxy, the Milky Way, or far beyond it. They are accelerated in the shock waves that inevitably follow such cosmic explosions, and are known as *cosmic* rays, since at one time all were thought to come from outside the solar system, in the broader universe, or cosmos. More than 100 cosmic rays speed through every square foot of our upper atmosphere each second of every day.

It was more recently found that while some, more properly called galactic cosmic rays or GCRs, do indeed come directly to us from far away, another class (initially called anomalous cosmic rays, or ACRs, and later, "pick-up ions") are born within the heliosphere.

ACRs are created when neutral atoms from the interstellar medium flow into the outer heliosphere. Those that penetrate into the near-Sun vicinity are ionized by solar short-wave radiation, and as charged particles are picked up by the magnetic field carried in the solar wind and accelerated to high speeds in passing through the termination shock. Some of these reach the Earth. There, they can be distinguished from other, galactic cosmic ray particles that reach the Earth by both lower particle energies and lower charge. ACRs are singly-charged ions with but one missing electron; GCRs, in contrast, have typically been stripped of all of their orbital electrons and carry a much higher positive charge.

Cosmic rays, whether ACRs or GCRs, are not "rays" at all—in the sense of rays of electromagnetic radiation in visible, ultraviolet, or infrared wavelengths—but ions: the same sorts of atomic particles that the Sun sends our way, all day, every day in the solar wind, and more sporadically from flares and CMEs. About 90% of all cosmic rays are *protons*; roughly 9% are the positively-charged nuclei of helium atoms (called alpha particles); and the remainder electrons and the charged nuclei of heavier elements. Most GCRs can be readily distinguished from particles of solar origin in that they are far more energetic.

GCRs that reach the near-Earth vicinity come in a wide range of energies. In passing into and through the heliosphere only the most energetic—those with energies greater than a few hundred MeV—are unaffected by heliospheric processes that slow them down, reducing the energy of a GCR by several hundred MeV during its passage through the heliosphere to the orbit of the Earth. Thus, ordinary GCRs that are detected at the Earth—whether coming from within our galaxy or beyond it—must have arrived at the boundary of the heliosphere with higher energies than what we observe here.

By the same token, GCRs that come from beyond our galaxy must have started their long journey with even greater energies. In order to slip through the combined magnetic field of the stars and other objects in our galaxy these intruders from truly distant worlds must begin their travels with energies in the range of about 1020 electron volts per particle (100 million trillion electron volts!). To these super-powered particles, breaching what are to them the relatively weak defenses of the heliosphere, and soon after that, our even weaker magnetosphere, must seem like a piece of cake.

THE PRICE OF ADMISSION IN ELECTRON VOLTS FOR CHARGED ATOMIC PARTICLES

PURPOSE	MINIMUM ENERGY REQUIRED, PER PARTICLE	IN GIGA (10^9) ELECTRON VOLTS
Entry Into the Galaxy	10^{20}	10^{11} GeV
Passage Into the Inner Heliosphere	3 x 10^8	.3 GeV
Unrestricted Entry Into the Magnetosphere • At the poles • At mid latitudes • At the equator	 GRATIS 10^8 10^{10}	 1 GeV 10 GeV

The Fate of Cosmic Rays

The microscopic examination of lunar rocks brought back to Earth by Apollo astronauts has shown that through at least the last 100 million years (since about the middle of the Cretaceous period of Earth history) the Moon has been bombarded by high energy cosmic particles at about the same rate as recorded on the Earth by neutron monitors today.

Since our close neighbor the Moon receives—per square foot—the same number of cosmic rays that strike the top of the Earth's atmosphere, this lunar finding of past cosmic ray flux applies to the Earth as well. But with no magnetosphere or atmosphere to buffer it, the Moon's long pummeled surface takes the full force of every solar or cosmic punch.

It is the Earth's atmosphere and not the magnetosphere that shields the surface of the Earth from the most energetic cosmic rays. Their energies are absorbed in collisions with atoms and molecules in the Earth's coating of protective air, much as an arrow, or a bullet, shot into water soon loses its thrust. Those cosmic rays that do make it to the surface are limited to the weaker, secondary particles that were created near the end of a downward cascade of collisions that started in the upper atmosphere.

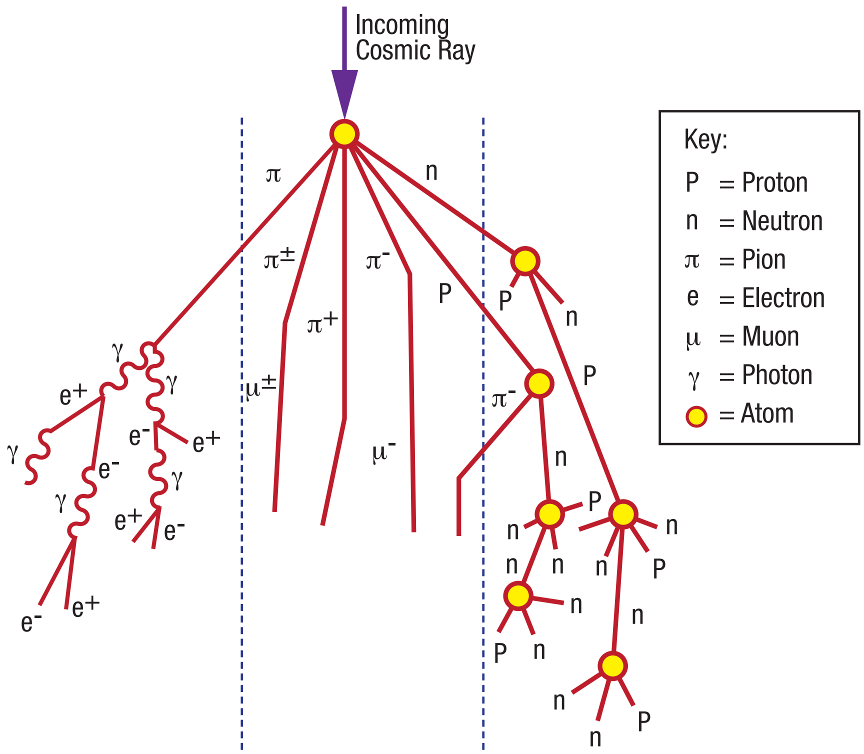
Taking most of the hits are atoms and molecules of nitrogen and oxygen: the most abundant constituents of the atmosphere, and these encounters are not inconsequential. The collision of a speeding, high-energy cosmic ray with a more lethargic atom or molecule is like the crash of a high-velocity bullet against a crystal goblet.

In the course of each of these violent impacts, the impacted atoms of air are shattered and torn asunder: producing a second generation of less energetic subatomic particles, each of which carries away a portion of the energy imparted by its parent cosmic ray. The heaviest and most energetic of the litter are protons and neutrons. Electrons are also produced, as are short-lived muons and pions that live for no more than a few microseconds.

These "daughter" or secondary cosmic ray particles extend the chain of collisions downward into the middle atmosphere, and ultimately a few make it to the ground. On the way down protons and neutrons soon suffer further collisions with other atoms of air, resulting in a <u>third</u> generation of sub-atomic particles. The protons and neutrons among these will in like manner generate a <u>fourth</u> generation; and so on, until all of the energy brought into the atmosphere by the parent primary cosmic ray has been spent: most of it—as with other families well endowed—by heirs.

This process of energy depletion through repeated collisions and divisions produces what is called a cosmic ray shower or cascade. They are initiated in the upper atmosphere and through repeated cascades reach down into deeper and denser layers of the atmosphere until the number of subatomic particles that are produced reaches a maximum and then begins to decrease.

Maximum production is reached at an altitude of but ten or eleven miles above the surface of the Earth: the very height at which the *Concorde*—like a daredevil leaping through a wall of flame—made its fleeting trips. Below that, as the atmosphere thickens, the generations of cosmic rays finally lose all their punch, but barely in time to spare us and all the other bottom feeders in the ocean of air in which we live.



The shower of secondary atomic particles and radiation produced by the collision of a single incoming cosmic ray (top, center) with an atom of oxygen or nitrogen (first yellow circle) in the upper atmosphere, ultimately distributing the cosmic ray's not inconsiderable energy among less energetic, stable and unstable nuclear atomic particles, radiation in photons, and electrons. Here the initial impact releases (right panel) a proton and neutron, each of which initiates further cascades by colliding with other atoms of air (yellow circles.) Also released are less stable nuclear particles known as pions and muons (middle panel) as well as electrons and electromagnetic radiation (left panel.)

Could we see one of these cosmic ray cascades unfold—high overhead on a starry night—it would look much like the bursts and spreading trails of colored light that elicit oohs and aahs during aerial displays of fireworks on the 4th of July: although in this case each pyrotechnic display would last no longer than the wink of an eye.

The flux of cosmic ray and solar particles that reach the Earth behave oppositely and are very nearly mirror images of each other: when one is up the other is down. When the Sun is more magnetically active and spotted, the number of secondary cosmic ray neutrons that reach the Earth is reduced by about 20%. When the Sun is less active, more are recorded. A repeated pattern of 22 years, in step with the solar magnetic cycle, is also apparent in the Earth's receipt of cosmic rays as an alternation in the characteristic shape of successive 11-year cycles of cosmic ray flux, apparent in plots of cosmic rays vs time. In plots of cosmic ray incidence vs. time, 11-year cycles that reach a distinct peak alternate with cycles that are flat-topped, i.e. exhibit a prolonged maximum.

The last maximum in the 11-year solar cycle was reached in 2001. Since then, while the number of sunspots was gradually falling, year after year, the flux of cosmic rays—recorded continuously by neutron monitors at high-altitude stations in Colorado, Vermont, Antarctica and a host of other sites—reached a cosmic ray *maximum* (and a sunspot *minimum*) in 2008.

Sunspots themselves have no direct effect on cosmic rays, but disturbances in the flow of solar wind plasma do. For the most part, these can be traced to the interaction between fast-moving CME plasma and the ambient solar wind, which occur more often in years of maximum solar activity, since CMEs are more energetic and more frequent then. At these times of greater turbulence, incoming cosmic particles are more likely to be scattered and deterred from reaching the Earth. When the Sun is less active the opposite is true.

RELATIVE NUMBER OF HIGH-ENERGY ATOMIC PARTICLES THAT REACH THE EARTH'S MAGNETOSPHERE

SOURCE ↓	RECEIVED AT TIMES OF MAXIMUM SOLAR ACTIVITY	RECEIVED AT TIMES OF MINIMUM ACTIVITY
From the Sun	**More**	Fewer
From the Cosmos	Fewer	**More**

We can also expect the Earth's receipt of galactic cosmic rays to vary, periodically, on a much slower scale as the Sun makes its orbit around the center of the Galaxy: a circle so large that it takes almost 250 million years to complete a single lap around it.

The longest record of cosmic ray flux at the Earth is taken from the analysis cited earlier of lunar rocks brought back during the *Apollo* missions of the 1970s. From these rudimentary natural diaries one can infer that the flux of galactic cosmic rays—with enough energy to leave their tracks on the face of exposed lunar rocks—has not changed very much during the 100 million year period (a little less than half a turn around our Galaxy) that is sampled in the exposed material.