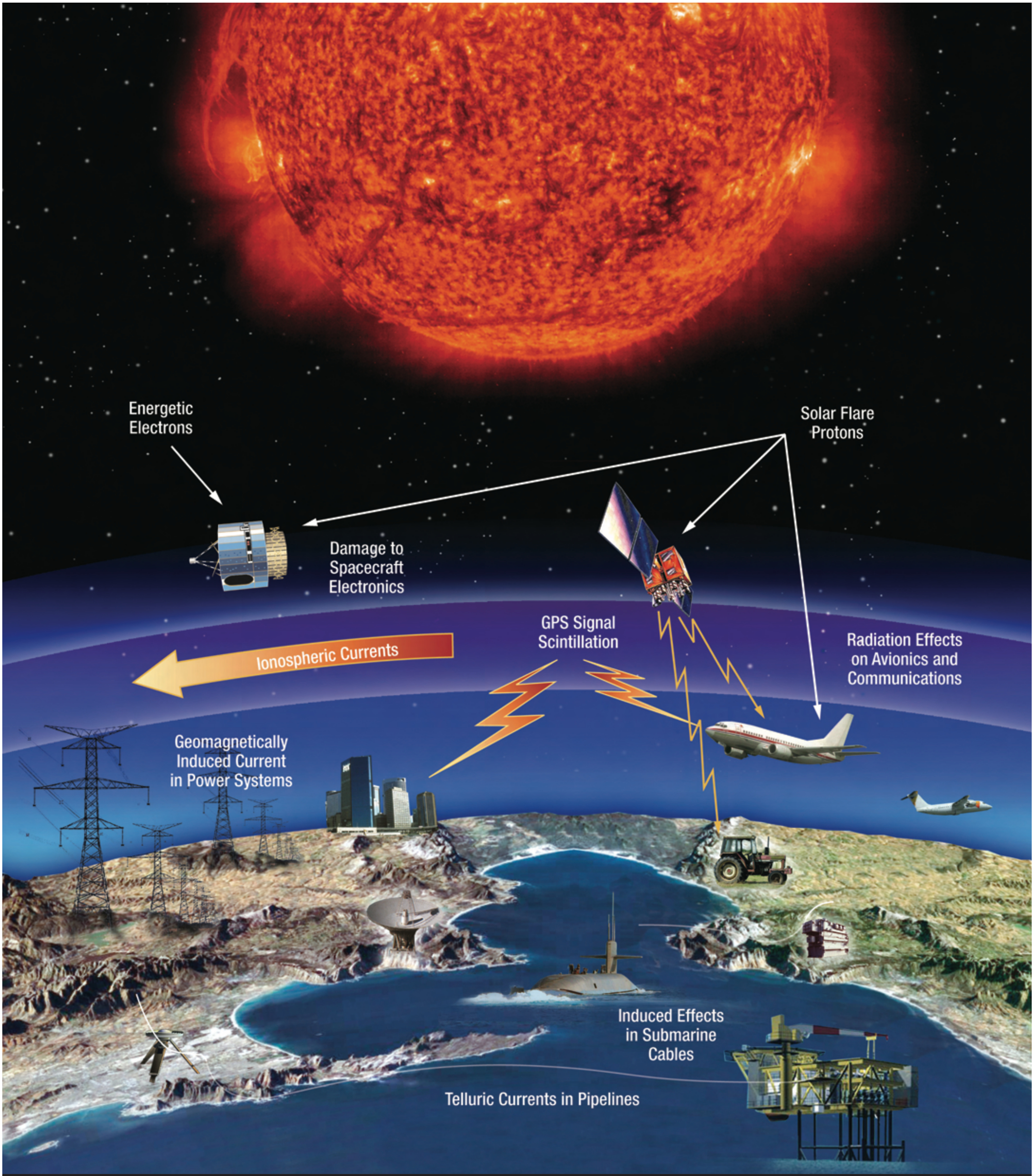

Some of the ways by which solar eruptions and the geomagnetic storms which they induce affect our lives and livelihood on the ground, beneath the sea, in the air and in near-Earth space.

EFFECTS ON HUMAN LIFE AND ENDEAVOR

What Is Affected

In what ways are we affected when solar disturbances alter conditions in the Earth's near-space environment, in the magnetosphere and ionosphere, the atmosphere, and the oceans and solid surface of the planet?

Two hundred years ago, when sunspots were all that was known of solar variability, it was suspected that their coming and going were in some ways affecting the weather and the number of auroral displays that were seen, athough neither connection had been verified. By 1950, however, when telegraphy, transoceanic cables, telephones, wireless radio, radar and more extensive electric power distribution systems had come upon the scene, the societal impacts of solar activity had reached far beyond possible ties to the weather into other areas of societal concern. Foremost among these were disabling effects on radio and other electronic communications, and disruptions of electric power distribution systems.

By the late 1950s, and particularly after our entry into space, the list of societal consequences rapidly increased in number and importance, as they have, almost exponentially, since then.

Today the heavy commercial and military reliance on spacecraft—particularly those in more hazardous high-Earth orbits—and the plans for a manned return to the Moon and for possible human exploration of distant Mars have vastly increased our vulnerability to the changing moods of the Sun. As has the switch in the last decade from custom-produced "space-hardened" electronic components to those that are available commercially, off-the-shelf.

In this section we summarize and then describe some of the specific ways through which the Sun's impacts on the Earth affect a broad range of human activities.

Some Specific Societal Effects

AIRCRAFT TRAVEL

Operational flight control and other aircraft communication outages;

exposure of passengers and crew on high altitude polar flights to mild dosages of CME-accelerated particles, high-energy particles from solar flares, and GCRs; and disruption or failure of essential ground-to-air and air-to-ground communications

HUMAN SPACE FLIGHT

Increased exposure of astronauts, both within a spacecraft or, with greater risk, while outside it, to high energy particles from solar flares and CMEs. During EVAs or when on the Sun-lit surface of the Moon or Mars, astronauts are also highly vulnerable to enhanced x-ray emission from the Sun

OPERATION OF SPACECRAFT AND SPACE EQUIPMENT

Electrical charging of the surface of the spacecraft resulting in degradation of the metallic surface; induced charging of cables and surfaces within the spacecraft, leading to deleterious impacts on the operation of computer memory and processors and to damage or failure of semiconductor devices in electronic components and other instruments; orbital perturbations and accelerated orbital decay due to the solar-driven expansion of the thermosphere; degradation of the surfaces of solar cells; disruption of spacecraft attitude-control; and interference with low-altitude satellite tracking

OBSERVATIONS OF THE EARTH FROM SPACE

Interruption and degradation of data used in preparing daily meteorological forecasts, in tracking and monitoring hurricanes and other storms, in forecasting expected crop yields, and for surveillance and other national security purposes

COMMUNICATIONS AND NATIONAL SECURITY

Ionospheric disturbance of radio transmissions of all kinds and in almost all radio-frequency bands, affecting nearly every form of electronic communication, including satellite telephones, network television, operation of communications satellites, transmissions to and from orbiting spacecraft, and essential military communications and radar systems. Other disturbances arise from induced electrical currents in long under-sea telecommunication cables, long-haul telecommunication lines, and certain fiber-optics systems

GEOGRAPHIC POSITION FINDING AND NAVIGATION

Errors and reduced accuracy in GPS systems affecting navigation and position finding at sea, in the air, and on the surface of the Earth; malfunction of other navigational aids; and the introduction of magnetic compass errors

ELECTRIC POWER TRANSMISSION

Power black-outs, brown-outs and disruption of electric power grids, triggered by solar-induced currents in power lines and overheating and eventual failure of power-line transformers; curtailing the cost-saving ability of electric power grids to move cheaper electricity from available sources to users at more costly sites

OPERATION OF OIL AND GAS PIPELINES
Solar-induced electric currents in long pipelines at high latitudes, leading to corrosion and the ultimate failure of metal and welded joints

GEOLOGICAL SURVEYING AND PROSPECTING
errors and reduced accuracy in geological survey work, including prospecting for minerals and oil, due to solar-driven perturbations and the impacts of magnetic storms on the Earth's surface magnetic field; operational failures in drilling operations that rely on the Earth's magnetic field for directional reference

REGIONAL AND GLOBAL CLIMATE
Increase in the mean surface temperature of the Earth and the surface and subsurface temperature of the oceans, affecting atmospheric circulation and precipitation; exacerbation or amelioration of other agents of climatic change, including El Niños and human-induced greenhouse warming

Exposure of Aircraft Passengers and Crews

Solar activity can affect the safety of high altitude jet aircraft flight in two different ways. The first and most often encountered is interference in essential ground-to-air and air-to-ground communications. The second is the exposure of aircraft passengers and crews to potentially-harmful high-energy atomic particles.

Passengers and crews in high-flying aircraft are fully shielded from potentially-harmful solar ultraviolet and x-ray radiation by the metallic skin of the aircraft, just as astronauts are shaded from more intense sunlight at spacecraft altitudes.

This is not the case, however, for energetic particles from solar flares, CMEs and cosmic sources that have made their way into the upper troposphere and lower stratosphere, where aircraft fly. For these fast-moving and extremely energetic particles, the metallic skin and frame of an aircraft present almost no obstacle at all. Sufficiently energetic cosmic rays and solar particles will also pass through the aircraft interior as well as clothing and human skin like high-speed bullets through a paper target, to continue on at high velocity into human tissue and cells.

There they can ionize some of the atoms of which living cells are made, and—in sufficient dosage—alter the structure of impacted cells, and through these changes introduce mutations in the ensuing generations that these cells produce. Sufficient exposure to this kind of so-called ionizing radiation, (whether at one time or accumulated in the course of many months or years) can produce different forms of radiation sickness and possibly lead to cancer.

The degree to which crews or passengers are affected on any jet flight depends on the flight trajectory, including altitude and the regions of the Earth over which it flies. Air travel at conventional jet aircraft altitudes and within middle or low latitudes—like most flights within the lower 48 states—are but little affected.

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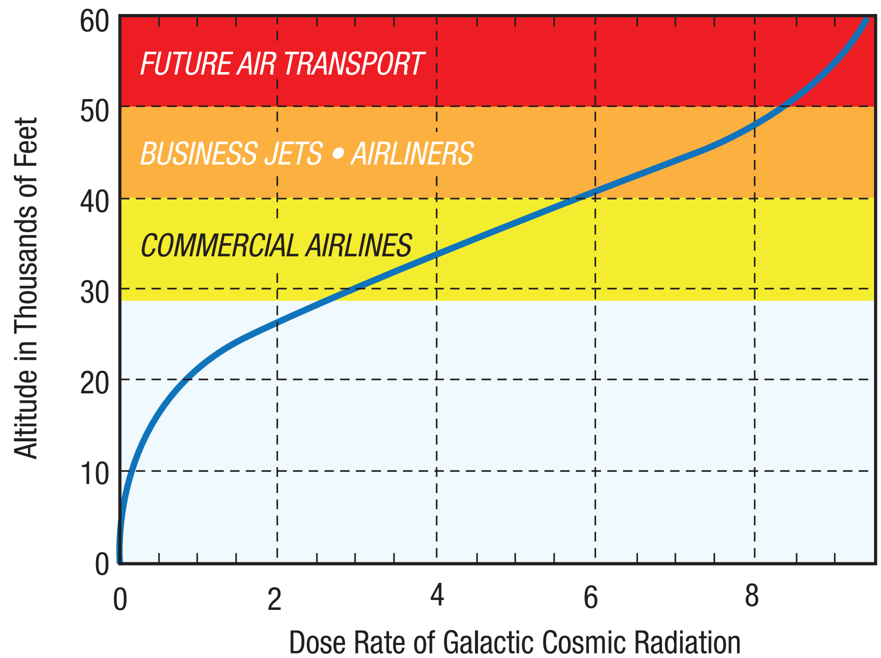
More at risk are flights that spend a significant amount of time over polar and sub-polar regions, where energetic solar particles more easily stream down into the atmosphere. Most of these incoming particles lose much of their original energy high in the atmosphere, through collisions with atoms and molecules of air, but some of the second generation particles that are produced in these collisions continue downward into the altitudes where jet aircraft fly.

The number of downward streaming secondary cosmic rays reaches a maximum at an altitude of about twelve miles or 66,000 ft: but a few miles above the highest altitude at which today's jet aircraft fly. Below that, depleted by thicker air and more frequent collisions among particles, the number begins to fall.

Thus, in the range of altitudes at which commercial, business, and military jet aircraft fly—between about 30,000 and 50,000 ft—the expected dose of secondary cosmic particles increases markedly with altitude. A jet aircraft climbing from 30,000 to 40,000 ft (the range of altitudes of most commercial airliners) triples its expected exposure to cosmic rays. Climbing above 40,000 to the rarified altitudes at which the next generation of commercial airliners will fly—between 50,000 and 60,000 ft—will increase the dosage by another factor of three or four.

A map of the world showing the expected dosage of energetic particles at a given jet aircraft altitude would portray an extensive zone of significant risk centered on each of the two magnetic poles of the Earth. Due to the considerable offset of the north magnetic pole (today about 1000 miles south and west of the North *rotational* pole) this zone of greatest exposure reaches farther down in latitude in western North America than elsewhere in the Northern Hemisphere.



The dose of damaging radiation from galactic cosmic rays expected at different aircraft altitudes, from the surface of the Earth to 60,000 ft., showing the altitude range at which different types of aircraft now operate. A prevailing trend in future aircraft planning and design is to operate at altitudes in the now little-used band between 50,000 and 60,000 ft. in order to increase the range of ever larger aircraft and to utilize less congested air space. Any change in this direction will sharply increase the exposure of aircraft passengers and crews to high energy galactic particles. The curve shown here applies to low and middle latitudes; the dosage will increase as a function of higher geographic latitude, with highest dosages in polar and sub-polar regions.

This southward bulge of the more hazardous zone affects all who travel at high altitudes over Canada and as far south as the Great Lakes and the northern tier of states in our own country. Most exposed are passengers and crews on long-distance, intercontinental flights—such as those from New York to Tokyo, or Seattle to London or Frankfurt—that follow great circle routes that carry them over sub-polar regions in northern Canada or Greenland. In the course of five of these polar crossings a passenger or crew-member will have typically absorbed an amount of high energy particle radiation that exceeds the maximum recommended *yearly* dosage.

The routes followed by the *Concorde*, which took it back and forth across the Atlantic at *middle* rather than high latitudes, mitigated some of the added risk that comes with flying at an altitude of about 58,000 ft (compared to 30 to 50,000 feet for conventional commercial airliners.) The *Concorde* was also helped in this regard by its supersonic speed which—like running instead of walking through the rain—considerably shortened the exposure time.

The radiation dosage encountered in most commercial jet-aircraft flights is no more than what one expects from a medical x-ray; although in a flight that happens to cross polar and sub-polar latitudes at the time when high-energy solar protons arrive, the dosage would considerably exceed that amount. In any case, in most single encounters of this kind, immediate risks to the health of passengers and crew are not severe.

These concerns increase with repetition, as in the case of passengers or crews who regularly or frequently fly on intercontinental flights that take them across these more exposed polar regions. Most at risk are pregnant passengers or crew members, aircraft crews in general, and the half million frequent fliers who log more than 75,000 miles—three times around the Earth at the equator—year after year.

The intensity of particle radiation at jet aircraft altitudes can be ten to fifteen times higher than normal after the eruption of major flares and CMEs, with highest dosages in those cases when streams of energetic particles from a major solar eruption happen to reach the aircraft while it is passing over polar and sub-polar regions. The most energetic of these particles are protons from major solar flares with single-particle energies in the range of a million to a billion electron volts. The more energetic of these can reach an aircraft in less than twenty minutes after the flare was first sighted, limiting the time available for aircraft to be diverted to reduce the impact of these particle incursions on air-to-ground and ground-to-air communications.

AIRCRAFT OPERATIONAL ALTITUDES IN RELATION TO ATMOSPHERIC FEATURES

ATMOSPHERIC FEATURE / ***TYPE OF AIRCRAFT***	**DISTANCE ABOVE THE EARTH'S SURFACE IN MILES**	**IN THOUSANDS OF FEET**
Average height of tropopause	6	32
Commercial airliners	*6 - 8*	*32-42*
Business jets	*8 - 10*	*42-53*
Tropopause over equatorial latitudes	9 - 10	48-53
Supersonic aircraft (Concorde)	*11*	*58*
Planned future air transport	*10 - 12*	*53-63*
Maximum dose of secondary cosmic rays	12.5	66
Deepest penetration of primary GCRs	25	132

The possible effects on health of accumulated exposure are of sufficient concern that airlines and military flights routinely alter flight paths and altitudes to minimize the effects of particle radiation on communications; maintain records of each pilot's and crew member's career exposure; and rotate flight crews so as to limit their cumulative total. For these reasons, the European Union has adopted laws that mandate a certain amount of radiation monitoring on commercial airline flights.

Risks to Manned Space Flight

Three perils await space travelers who venture beyond the atmospheric and magnetospheric shields that for billions of years have allowed life to evolve on a planet immersed in a wholly hostile environment.

The *first* is the obvious drop in air pressure as one rises higher and higher above the surface of the Earth, and with it, a rapidly dwindling supply of oxygen to breathe. The *second* is more direct exposure to the full intensity of solar electromagnetic radiation, from the shortest to the longest wavelengths but particularly the highly energetic and penetrating extreme-ultraviolet and x-ray radiation from the Sun, which we never feel on the surface of the Earth. The *third*—most dangerous to life and health and hardest to avoid—is a direct exposure to streams of highly energetic atomic particles that arrive from solar disturbances and cosmic sources.

The Ocean of Air

Like fish in water, we can survive without artificial aid only at the bottom of an oxygen-rich ocean of air. Our ability to ascend safely above this abyssal depth—to the top of the atmosphere or even part way there—will always require that we bring with us our own pressurized atmosphere.

In the range of altitudes at which jet aircraft fly—seven or eight miles above the surface—air pressure and available oxygen are depleted by factors of four to six compared to conditions at the level of the seas. There—as in spacecraft operating at heights where ambient pressure and available oxygen have fallen by factors of more than a million—conditions essential for life are met by pressurizing and continually replenishing the air within the aircraft cabin.

On those occasions when astronauts venture *outside* their hermetically-sealed spacecraft—as during EVAs or on the surface of the Moon or Mars—the necessary environment is reproduced by pressurizing their air-tight space suits, helmets and gloves to atmospheric levels, and by carrying with them a portable oxygen supply.

Enhanced Ultraviolet and X-Ray Radiation

The threat from solar ultraviolet and x-ray radiation—which increase in intensity the higher we go—is more easily kept at bay.

Near-, intermediate- and extreme-ultraviolet radiation is able to penetrate the skin, damaging both the epidermis and the living tissue beneath it. Ultraviolet radiation is also particularly damaging to the eyes, and to the immune system. The aluminum body of an aircraft or spacecraft is more than adequate to block the full spectral range of the ultraviolet, as is the material of which windows in either of these are made. When outside the spacecraft, an astronaut's space suit, helmet and highly-reflective visor provide an equivalent level of protection against direct solar ultraviolet radiation.

Solar X-Rays

Solar x-rays, which are considerably more energetic than those employed in medicine, dentistry and airport security systems, are more hazardous than ultraviolet radiation and not as easily blocked.

As has been known and put to use for more than 100 years, clothing and flesh are transparent to x-rays. This is also true of much denser materials when directly exposed to the more energetic x-rays that come from the Sun. It is also known that a sufficiently long or cumulative exposure to x-rays—and particularly the more energetic—can damage and alter the further division of human cells, in the same way that energetic particles do: by ionizing some of the atoms of which they are made.

When within the metal shell of a spacecraft, astronauts are adequately shielded from both far-ultraviolet and x-ray radiation. The risk comes during extra-vehicular activity or when an astronaut in a space suit permeable to x-rays finds herself or himself on the sunlit surface of the Moon or Mars at a time when a major solar flare erupts. Unless cover is immediately found, the time of direct exposure to x-rays could last up to an hour or more: as compared to the fraction of a second employed in medical and dental x-rays. Moreover, the area potentially exposed is more extensive: not one's jaw or lungs or forearm, but everything there is from head to toe.

A Sun Intensely Bright

One should never look directly at the face of the Sun, unless it is severely dimmed in some way or seen through a very dark and dense optical filter.

When seen from above most or all of the ocean of air, the potential risks are even greater.

In space, where there is no atmospheric absorption or scattering of sunlight, the disk of the Sun is definitely brighter, and much more so at the violet end of the visible spectrum. It was with this in mind that the helmets worn during EVAs—and by *Apollo* astronauts on the Moon—are equipped with highly-reflective, gold-mirrored visors.

There is as well the potential of a kind of snow-blindness, if anyone *within* a spacecraft should catch an inadvertent glimpse at the first rays of the Sun at sunrise: an event that is repeated about every ninety minutes, or sixteen times each day for those in lower orbits about the Earth. And each time—as on the road to Mandalay—the dawn comes up like thunder.

In truth—as with many other familiar things—there is no dawn in space. Instead, the first sliver of the rising Sun appears abruptly and without warning, for in the absence of an atmosphere there is no gradual bluing of the coal-black sky or any colored glow on the horizon to herald its coming, and to condition the dark-adapted eye. Moreover, when it appears, the Sun also climbs above the horizon far faster—as in a speeded-up movie—since the apparent motion of the Sun through the sky is, when in orbit about the Earth, driven not by the 24-hour rotation of the planet but the 1½ hour orbit of the spacecraft around it.

For an astronaut who—while looking out, perhaps, at the black starlit sky—chances to see the first bright edge of the fast-rising Sun it would seem like the shock of a flash-bulb in a totally darkened room, though in this case as bright as a welder's torch.

Solar Energetic Particles and Cosmic Rays

Because of their mass and extremely high speeds, atomic particles carry very high energies and are therefore far more lethal than the damaging ultraviolet or x-ray electromagnetic radiation that comes from the Sun. They are also much harder to protect against, for not only space suits and helmets but the materials from which spacecraft are made present few obstacles to these speeding bullets.

Astronauts have even "seen" some of these invasive high energy particles while in space. Beginning with the first *Project Mercury* flights, astronauts in orbit about the Earth have reported seeing flashes of bright light, which are visible whether their eyes were open or closed. These were soon identified as the tracks of cosmic rays or solar energetic protons that produced what is known as Cêrenkov light on their way through the astronaut's head: more specifically, through the viscous medium that fills the eyeball. Cêrenkov radiation, which has been known since 1939, is a form of light created by charged atomic particles when they pass through a transparent substance at a speed greater than the velocity of light in that medium.

Particles from solar flares or cosmic sources with energies from ten to several hundred million electron volts (MeV) can easily penetrate the thin metal skin and frame of a spacecraft: which, as in airplanes, is designed with minimum weight in mind. A 100 MeV proton traveling at velocities close to that of light itself can pass through a good 1½ inches of aluminum—about three times the thickness of the steel hull of the Titanic—before it is stopped. Lighter and hence weaker 3 MeV electrons—of the sort that swarm in great numbers within the Earth's radiation belts—can make it through a sheet of aluminum a quarter-inch thick. And the most energetic particles—galactic cosmic rays (GCRs) with energies as great as a billion or more electron volts (GeV), are for most situations in space essentially unstoppable.

Thus the health hazard of greatest concern in manned spaceflight, as in high-altitude jet aircraft travel, is exposure to high-energy solar atomic particles and galactic cosmic rays.

The expected dosage in a high altitude aircraft—even over the poles or during major solar flares—is much reduced, since by the time these speeding particles (or more correctly, their descendants) reach the altitudes at which conventional aircraft fly, they have lost much of their original prodigious energy through encounters with atoms and molecules of air on their way down.

This is not the case for spacecraft. What is more, the expected dosage increases considerably with travel in higher orbits that take them into or near the Earth's radiation belts: and more so beyond the protective arms of the magnetosphere.

Another hazardous zone for spacecraft that travel in Earth orbits within or below the magnetosphere is the South Atlantic Anomaly, or SAA: a portion of the Earth's magnetic field located over southern South America and the South Atlantic Ocean where the field strength is considerably reduced. In this danger zone—which might seem reminiscent of the Bermuda Triangle were it not in this case real—energetic particles in the Earth's inner radiation belt are able to penetrate more deeply into the thermosphere, to altitudes where so many spacecraft in near-Earth orbits fly.

FLIGHT PATHS OF AIRCRAFT AND SPACECRAFT IN ORDER OF INCREASING EXPOSURE TO HIGH-ENERGY PARTICLES AND RADIATION

FLIGHT PATH AND ALTITUDE	EXAMPLE FLIGHT VEHICLES	HAZARD	EXACERBATING FACTORS Defined in the Legend Below
PRESENT DAY JET AIRCRAFT [6 - 10 miles altitude]	Commercial Airlines, Corporate and Military Aircraft	Cosmic Rays, Solar Protons	Polar Routes, CMEs
NEXT GENERATION JET AIRCRAFT [10 - 12 miles]	Commercial airlines, military aircraft	Cosmic rays, solar protons	Polar Routes, CMEs
EARTH ORBITS BELOW THE MAGNETOSPHERE: Low Earth Orbits (LEO) [150 - 500 miles] at low latitudes	Space Shuttle, Hubble Space Telescope (375 mis)	Cosmic rays, solar x-rays and protons, trapped particles	SAA, EVAs, CMEs, MAG STORMS
LOW EARTH ORBITS (LEO) at higher latitudes [150 - 500 miles]	International Space Station	Cosmic rays, solar x-rays and protons, trapped particles	SAA, EVA, CMEs, MAG Storms
EARTH ORBITS IN CLOSE PROXIMITY TO THE LOWER RADIATION BELT: Medium Earth Orbits (MEO) [16,000 miles]	Fleet of GPS Spacecraft	Trapped particles, solar x-rays and protons, cosmic rays	MAG Storms, CMEs
SPACE TRAVEL WITHIN THE RADIATION BELTS: GeoSynchronous Orbits (GEO) [22,200 miles]	Telecommunications Satellites; Manned Spacecraft en route to the Moon or Mars	Cosmic rays, solar protons, trapped particles	MAG Storms, CMEs
SPACE TRAVEL BEYOND THE MAGNETOSPHERE: Enroute to, or on the surface of the Moon	Apollo Spacecraft and Lunar Modules; Planned Missions to the Moon	Cosmic rays, solar x-rays and protons	Duration, EVAs, CMEs
ENROUTE TO, OR ON THE SURFACE OF MARS	Projected Human Exploration of Mars	Cosmic rays, solar x-rays and protons	Duration, EVAs, CMEs

LEGEND

CMEs	During or following a major solar flare or CME
EVAs	During extra-vehicular activity of any kind
MAG	Occurrence of a major geomagnetic storm
Polar Routes	Aircraft flights that cross polar or high latitude regions
SAA	Passage through the South Atlantic (magnetic) Anomaly
Duration	Manned space missions of long duration

Among the affected are the *Space Shuttle*, the *International Space Station*, and a large number of other unmanned spacecraft. As an example, one of the instruments on the *Hubble Space Telescope* was found to be so disrupted in passage through the SAA that it was routinely switched off during each of the Hubble's brief passages through this zone.

The Physiological Effects of Ionizing Radiation

The risks of exposure to very energetic atomic particles lie in their ability to tear electrons from (or ionize) atoms in cells that make up human tissue. Because of this, cosmic rays, solar energetic particles and even solar x-rays are often described as *ionizing radiation* (to distinguish their effects from those of solar *electromagnetic radiation* in the infrared, visible, ultraviolet portions of the spectrum.) They can do this whether or not the impacting particles carry an electric charge.

The ability of speeding atomic particles to strip electrons from atoms in living tissue depends chiefly on their energy. In terms of their effect on life, the chargeless neutrons that are released as secondary cosmic rays pose as great a hazard as particles of equal energy that carry a positive or negative charge.

When neutral atoms in living cells are ionized, the chromosomes and DNA within them are altered in ways that can lead to cellular mutations and the risk of cancer.

Exposure to extreme doses of ionizing radiation can produce other, more immediate effects: skin burns which are slow to heal, cataracts, nausea, vomiting, damage to the nervous system, and depletion of the immune system. In short: the symptoms of radiation sickness experienced by cancer patients receiving radiation therapy, or more severely by the many victims of atomic bomb explosions over Hiroshima and Nagasaki some sixty years ago.

The Importance of Dosage

The extent to which those in exposed aircraft flights or in space are ultimately affected is determined by both the *amount* of radiation received at any time (as during a medical x-ray, or a half hour's exposure to solar energetic particles) and the *cumulative total* of ionizing radiation encountered in the course of one's life.

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We all receive some ionizing radiation every year, no matter where we live or what we do. Should we undergo medical or dental x-rays, we are exposed to a brief and localized dose. More significant in most cases is an ever-present dose of ionizing radiation from some of the rocks and minerals and soils that are beneath and all around us, from which in the course of a year it is possible to accumulate a dosage of up to ten medical x-rays.

Aircraft crews and passengers receive a small amount of potentially-damaging radiation in every flight that crosses polar and sub-polar regions, which include most non-stop flights to and from Asia from northern American airports and many to destinations in northern Europe. Astronauts are exposed to greater levels from cosmic rays and other energetic particles each time they venture into space.

The recommended *maximum annual dosage* for anyone is equal to about ten medical x-rays. A round-trip flight over a polar route between New York to Hong Kong will on average accrue an exposure equivalent to about two of them. In space the dosage increases dramatically: from cosmic rays, solar energetic particles and from energetic particles trapped in the Earth's radiation belts. The total dosage is a function of the flight path, the time spent in EVAs, the state of solar activity, and the overall duration of the space flight.

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Almost all manned space flights, including the relatively short flights of the *Space Shuttle* and the far longer stays on the *Space Station*, have remained at altitudes of no more than about 300 miles above the surface: well below the Earth's radiation belts and also, for most solar particles, within the protection of the Earth's magnetosphere.

Under these circumstances the cumulative exposure to ionizing radiation of those on board—though much greater than what we receive on the ground or the air—has been shown to be of little consequence, and as yet, no cause for alarm. For example, exposure to cosmic rays during a record one-year stay in low Earth orbit aboard the *Mir* spacecraft was estimated to increase the risk of future cancer for cosmonauts on board by about one percent. Experience has shown that under ordinary solar conditions, orbital flight below the level of the radiation belts and magnetosphere are not a major health concern.

However, for a manned spacecraft traveling *beyond* the magnetosphere during a particularly intense solar flare, or worse, during a long-lasting CME particle event, the ionizing radiation received each hour within the spacecraft can equal that of six or seven *thousand* chest x-rays, with even greater consequences if caught outside, on EVA.

This has yet to happen, but it could have and almost did during the five-year period of NASA's manned *Apollo* missions to the Moon: eleven flights, each lasting from ten to fourteen days, which for the first time carried human cargo beyond the protection of the magnetosphere and into the full force of solar and cosmic particles.

The Disaster That Almost Happened

The first, last and only space ventures of this kind were the nine *Apollo* missions conducted in late 1968 through early 1972, each of which completed the 480,000 mile voyage to the Moon and back.

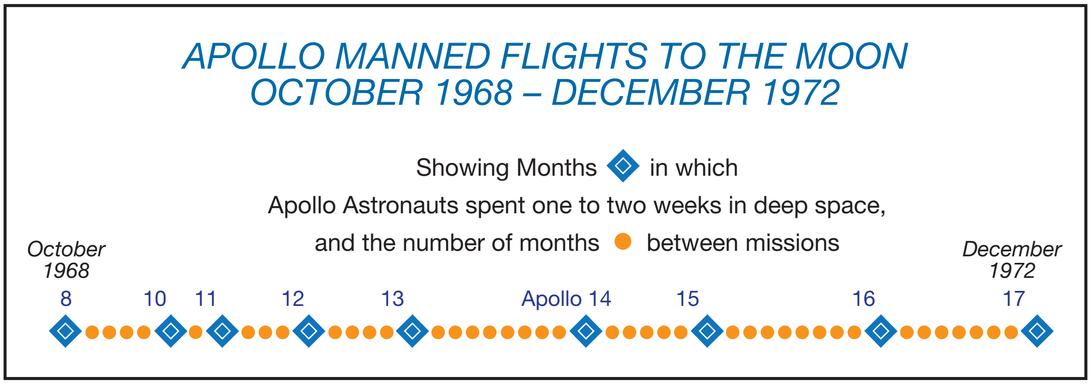
Off and on in this 51-month period—which followed the peak of a moderately strong sunspot cycle—25 astronauts, on flights spaced on average about six months apart, lived and worked in deep space, shielded only by the *Apollo* command module spacecraft and the smaller and the less shielded lunar lander.

MANNED SPACE FLIGHTS THAT HAVE GONE BEYOND THE MAGNETOSPHERE

MISSION	CREW	LAUNCH DATE	TIME SPENT IN DEEP SPACE	TIME SPENT ON THE MOON
Apollo 8	F. Borman J. Lovell W. Anders	1968 Oct 11	6 days	None
Apollo 10	E. Cernan J. Young T. Stafford	1969 May 18	8 days	None
Apollo 11	N. Armstrong M. Collins E. Aldrin	1969 July 16	7 days	21 hrs, 36 mins
Apollo 12	C. Conrad R. Gordon A. Bean	1969 Nov 14	10 days	31 hrs, 31 mins
Apollo 13	J. Lovell F. Haise J. Swigert	1970 Apr 11	6 days	None
Apollo 14	A. Shephard S. Roosa J. Mitchell	1971 Jan 31	9 days	33 hrs, 31 mins
Apollo 15	D. Scott A. Worden J. Irwin	1971 July 26	12 days	66 hrs, 55 mins
Apollo 16	J. Young* T. Mattingly C. Duke	1972 Apr 16	12 days	71 hrs, 2 mins
Apollo 17	E. Cernan* R. Evans H. Schmitt	1972 Dec 7	13 days	75 hrs

*Crewed Apollo 10 as well

In all, these nine bold missions kept astronauts immersed in this unknown and potentially hazardous environment for a total time of almost three months. In terms of possible major impacts from the Sun, the one to two-week missions placed these deep-space travelers in harm's way for about 6% of the time during a 51-month period of moderate activity in the life of the Sun: the intervals depicted with blue diamonds in the following chart.



In addition, for a total time of 12½ days men lived and worked on the wholly unprotected surface of the Moon. And although they never wandered far from the lunar lander, it would have offered no protection at all against extremely energetic solar particles that rained down on the surface of the Moon. The only safe place would have been against a shaded, sloping wall of a lunar crater, were such a refuge close at hand. Even then, a place in the shade would not offer full protection against incoming charged particles from the Sun, since the earliest particles arrive along curved paths and the others from all directions (other than up from the ground), as a result of scattering by magnetic fluctuations encountered en route from the Sun.

While many smaller flares and unseen CMEs occurred during the period of the *Apollo* flights, there was but one anomalously-large solar proton event.

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In early August of 1972, well into the declining phase of solar cycle 20 and about midway in the four-month down time between the *Apollo 16* and *17* missions, the Sun displayed an abrupt and unexpected increase in solar magnetic activity. The result was ten days that shook the world: intense solar flares and CMEs, one after another. From this prolonged barrage came a steady stream of solar energetic protons (SEPs) that provoked magnetic storms, auroral displays, and severe disruptions of radio communications and electric power transmission.

Solar flares most often last for a matter of minutes followed by more extended particle showers that arrive at Earth several days later. But the super flare that was seen on the Sun in the early morning of Monday, August 7, 1972 lasted more than *four hours*, making it one of the largest and most intense of any that have ever been observed. In the same 10-day period CMEs showered the Earth for extended periods of time. This combination of intense flares and CMEs exposed our planet in those few days in early August to record-breaking levels of high-energy particles.

Solely by chance, the *Apollo 16* mission had returned safely from the Moon about four months *before*, on April 27; and the next and last of the series, *Apollo 17*, left for the Moon about four months *later*, on December 7.

Had there been a significant delay in *Apollo 16*, a moved-up *Apollo 17*—or had the Sun erupted as severely but a few months earlier or later—the three astronauts on board would have been exposed for hours or even days to potentially lethal ionizing radiation, whether they were at the time within the command module, the less shielded lunar lander, or on the surface of the Moon.

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The heaviest dose during this period would have come principally from long-lasting streams of energetic protons from CMEs, combined with the shorter exposure to similar particles from the August 7 flare. During the first half-day of their exposure to atomic particles from that one event, the *Apollo* astronauts would have exceeded the recommended maximum *yearly* dosage of radiation to the eyes and internal organs and the maximum *lifetime* dosage to the skin. As a result of this exposure they would almost certainly have experienced severe symptoms of radiation sickness, which for some or all of the three adventurers could have proven fatal.

The initial blast of high-energy protons from so intense a flare would have reached the spacecraft and the surface of the Moon within twenty minutes after the visible explosion was seen at solar observatories around the world. But the actual warning time for the *Apollo* astronauts would have been reduced to less than twelve, because of the time it takes for the light that announced the flare to reach the Earth. Moreover much or all of this would have been spent in human reaction and response times, and in communications among solar observers, flight controllers, and the spacecraft crew.

In these few minutes what must be evaluated is first the relative intensity of the flare; second, whether particles expected from it are likely to strike the Earth-Moon vicinity; and third, the nature of the risk to *Apollo* astronauts and the mission itself.

At the very most the astronauts might have had a few short minutes to find whatever cover they could, before the first wave of particles came upon them. In the command module—or worse, the lunar lander—there would have been no place to hide from the most energetic solar particles. Were they working on the surface of the Moon when the urgent warning was received, they would have found only limited protection from the first-arriving particles were they to hide behind a shaded wall of a lunar crater, for reasons cited earlier. But this is not the case for the many others that follow the initial blast. These particles, which can arrive over many hours or days in the case of CMEs, are deflected or scattered by fluctuations in the heliosphere and hence arrive from all directions in the sky.

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Presently-planned round-trip flights to the Moon, probably lasting about two weeks, and the far longer stays envisioned in the recent decision to establish a permanent base there will again carry the potential of severe hazards from ionizing radiation: because of the period of time spent outside the Earth's atmosphere and magnetosphere; the finite probability in most seasons of the solar cycle of intense flares or CMEs; and the engineering challenges involved in providing adequate shielding against GCRs and the most energetic solar protons while in deep space.

Envisioned trips to Mars, lasting from two to three years and with stays of up to eighteen months on the exposed Martian surface, present problems far more severe. This is in part because astronauts would be exposed to the full fury of the Sun not 6% of the time, as was the case in the four years of *Apollo* flights, but *all* of the time through a continuous period of three to four years, in addition to the continuous exposure to very high energy galactic cosmic rays.

The greater risk to life and health on any *extended* mission beyond the Earth's atmosphere will be the accumulated dosage of galactic cosmic rays that are more energetic by far than solar particles and which arrive from everywhere, every day and around the clock. In addition, on excursions as long as these—50 to 75 times longer than those to the Moon—the voyagers are almost certain to experience at least one and more likely several major solar flares, and countless CMEs that accelerate high-speed solar wind particles to very high energies.

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To avoid the certain hazard of prolonged cosmic ray exposure—and to reduce the odds of a solar catastrophe—long missions, particularly, will require a practical solution to the yet-unsolved problem of providing adequate shielding. The first that comes to mind is probably that of sheathing the spacecraft living quarters in heavy metal many inches thick, or a blanket of water at least 15 feet deep with a mass of more than 500 tons, which is nearly 20 times what the present space shuttle can carry. Technical and weight considerations also pose severe engineering challenges for the notion of containing the spacecraft in its own protective magnetic field, which would need to be more than half a million times stronger than the Earth's field for shielding against GCRs.

Other options, now under study or consideration include the development of much larger rockets that would reduce exposure by speeding the journey to and from the Moon or Mars, and a proposal to enclose the inhabited portion of the manned spacecraft within a protective shell formed by a wrap-around cluster of long cylindrical tanks filled with liquid hydrogen. The nucleus of each hydrogen atom is a single proton, which is a relatively efficient absorber of some of the kinetic energy of particles—like cosmic rays—that happen to collide with it. By this scheme, the heavy cargo of liquid hydrogen fuel that must be taken along to lift the returning spacecraft from the surface of Mars would serve an additional, second purpose: as a partial buffer to protect against high energy cosmic rays during both the long outward voyage and the even longer stay on Mars. But all of these are as yet untried.

The serious threat of lengthy exposures to high energy cosmic rays—and the difficulty of shielding against them—may indeed make it more prudent to schedule extended manned missions like those to Mars during years of *high* rather than low solar activity. The bases for this are that when the Sun is most active the flux of galactic cosmic rays drops by 20% or so; and the fact that particles accelerated by CMEs and from flares—while considerably more prevalent then—are less energetic and therefore relatively easier to shield against.

The hazards of lethal cosmic rays may prove to be the principal obstacle to extended manned missions of any kind, including long-envisioned human exploration and colonization of the cosmos.

Impacts on Spacecraft, Space Equipment and on Observations of the Earth From Space

All things launched into space enter a hostile world. When a spacecraft reaches the exosphere—at an altitude of about 300 miles—it is directly exposed to EUV and x-ray radiation. As it continues its upward path—first within and then beyond the magnetosphere—it is more fully exposed to high energy solar particles; to the piercing rain of even more energetic atomic particles from distant cosmic eruptions; to violent gusts in the solar wind; and to sudden and potentially catastrophic bursts of highly energized atomic particles from solar flares and CMEs: the hurricanes and tsunamis of the heliosphere.

There are today some 850 spacecraft operating within this exposed environment, put there at a total cost of more than 100 billion dollars to serve military, civic, scientific, and commercial needs. The U.S. now owns or operates slightly more than half of these.

About 100 are there to support national security, surveillance, and military operations. A similar number gather unclassified data on all aspects of the Earth and space for the various federal agencies, including NOAA's weather and climate services, NASA, and the Departments of Agriculture and the Interior. But by far the largest fraction fall in neither of these two categories, but within the commercial sector, serving the burgeoning satellite communications industry.

Interruptions, or significant damage of any kind to this combined fleet of spacecraft can directly affect many aspects of modern life, and they happen all the time. Among the impacted areas are meteorological, oceanographic and geophysical observations taken from instrumented spacecraft, including the pictures of clouds and weather systems seen on cable or the nightly news; satellite telephones and most telephone land lines; geographic positioning systems; the relayed signals that allow broadcast television and satellite radio, police and emergency communications and the transfer and rapid exchange of commercial information involving transactions such as credit card purchases, stock exchanges, and automated teller machines; marine and aircraft navigation and aircraft traffic control; police and emergency communications; and a host of national security functions, including the minute-by-minute tracking of satellites and space debris.

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Bursts of energized electrons, protons and heavier ions from solar flares and CMEs are fully capable of damaging or disrupting the operation of many common components of space equipment. Among them are circuit boards, computers, computer software and storage devices, electrical and electronic cabling, solar cells, and photo-sensors. The same can happen when streams of high-speed solar wind provoke geomagnetic storms; when the spacecraft finds itself near or within the Earth's radiation belts; or from the continuous barrage of high-energy cosmic rays.

As noted earlier, the cost-driven shift from custom-produced "hardened" components to those bought off the shelf has greatly increased the vulnerability of spacecraft and space equipment to solar events. As has the trend toward miniaturization of computers and other electronic instruments.

Individual components of computer and other micro-electronic equipment are—unlike our own bodies—vulnerable to single particle events, with immediate impacts on the system in which that element is a part. In contrast, the primary concern in manned space flight is not so much individual events but the *accumulated dosage* of ionizing radiation.

Times of Particular Hazard

Because flares and the fastest CMEs occur more often when the Sun is more active, the most vulnerable times for spacecraft and space equipment—whether in orbit around the Earth or far beyond it—are the four or five years during and following the peak of the 11-year cycle, when solar eruptions sufficiently large to disrupt satellite operations will occur as much as 15% of the time. The effects of satellite drag are also greatest in years of high solar activity.

At the same time, while far more frequent when the Sun is more active, there is no respite from CMEs, which occur throughout the solar cycle. What is more, high-speed streams of plasma in the solar wind, which can accelerate charged particles in the Earth's radiation belts, are more prevalent when the Sun is *less* active. Because of this, potential damage to spacecraft and space equipment, though greater in years of maximum activity, is possible in all phases of the solar cycle.

Spacecraft that travel beyond the protection of the upper atmosphere and magnetosphere face an abrupt jump in the number of potentially-damaging solar particles when CMEs and flares occur. For those within the protection of the magnetosphere—where most spacecraft operate—these impulsive solar events can exert a similar effect, either directly or by increasing the numbers of energetic particles held within Earth's radiation belts.

CMEs also reshape the form of the magnetospheric shield, pushing it closer to the Earth on the Sun-facing side and blowing the cover, in a sense, for spacecraft in higher, geosynchronous orbits at altitudes of about 22,200 miles. These and high-speed solar wind streams can also provoke magnetic storms by accelerating particles in the Earth's inner radiation belt.

Flight Paths of Greatest Risk

The level of risk to spacecraft and space equipment is very much dependent where they operate. The most hazardous are trajectories that take it (1) into or near the radiation belts; (2) beyond the Earth's magnetic field; (3) in polar orbits; or (4) in any inclined, equatorial orbit that passes through either sub-polar regions or the South Atlantic Anomaly, where the Earth's field is notably weaker.

By far the most hazardous are those that spend time in the heart of the Earth's radiation belts or leave the protections of the Earth altogether. In addition to past and planned manned missions to the Moon and possibly to Mars, these include the many unmanned spacecraft that have been sent out to explore and monitor conditions in near-Earth space, and those commissioned as remote explorers of the Moon and planets and other objects within and beyond the solar system.

Spacecraft at the Lagrangian Points of the Sun-Earth System

Other instrumented spacecraft operate in high-Earth orbits that take them far beyond the outer periphery of the magnetosphere. The *Solar and Heliospheric Observatory*, or *SOHO*, has for more than ten years circled the Sun at a fixed distance from the Earth of about 940,000 miles—about 1% of the distance to the Sun—while always remaining on the Sun-Earth line.

The *ACE (Advanced Composition Explorer)* satellite, which samples conditions in the solar wind and gives advance early-warnings of conditions within approaching streams of solar particles, is another spacecraft that operates at this unique and faraway location: a place of neutral gravity between the Sun and the Earth-Moon system known as the L1 Lagrangian point, in honor of its predictor, the French mathematician Joseph-Luis Lagrange (1736-1813).

It was Lagrange's solution to a theoretical problem in mathematics that identified five unique "neutral points" in the combined gravitational fields of the Sun and the Earth-Moon system where a body should experience no net gravitational force. The most accessible of these, today known as L1, was empirically tested and put to practical use for the first time 184 years after his death.

At this place and distance the pulls of gravity from the closer and lighter Earth and Moon are neutralized by the gravitational tug in the opposite direction from the massive but more distant Sun. Here a spacecraft is in essence weightless, neither drawn back to the Earth nor from it toward the Sun. And with no place to fall, if brought to a stop it will remain in that vicinity: as though fixed to a rigid spoke that connects the center of the Earth to the Sun.

The pulls of gravity at the Lagrangian points are not perfectly stable, however, due to the non-circularity of both the orbit of the Earth and that of the Moon. As a result, spacecraft such as *SOHO* and *ACE* trace out small orbits of their own, with periods of about six months, that are centered on the L1 point. The cost of these orbital imperfections on the operation of spacecraft residing there is a need to spend on-board fuel to make minor corrections in their position, in order to keep them on station, lest they drift beyond the L1 zone into their own independent orbit around the Sun.

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A distinctive set of more than 200 minor planets called the Trojan asteroids are among other astronomical bodies that have long been affected by the mathematical singularities that Lagrange discovered. In the asteroid case the two objects whose gravitational attractions balance each other at five Lagrangian points are the Sun and Jupiter. The Trojan asteroids circle the Sun like Jupiter, in roughly 12-year orbits, held in the vicinity of the L1 Lagrangian point in this *other* three-body system. They too are made to oscillate in small circles about that mathematical point, due in part to the gravitational disturbances of the many moons of Jupiter.

Polar Orbits and the South Atlantic Anomaly

When spacecraft in polar orbits pass through regions where open field lines extend outward from the magnetic poles of the Earth they cross a region where potentially-damaging atomic particles make their way down into the upper atmosphere. Also in harm's way are those in inclined equatorial orbits that carry them through the South Atlantic Anomaly, where an enfeebled magnetic field allows the Earth's inner radiation belt to expand downward into their range of altitude.

Geosynchronous and Geostationary Orbits

The most vulnerable of flight trajectories that are kept *within* the protective arms of the magnetosphere are the geosynchronous and geostationary orbits at an altitude of 22,200 miles that keep spacecraft above a specific region on the Earth's surface. Included in these is the ever-growing number of commercial telecommunications satellites, as well as many scientific and other payloads. Under most conditions, spacecraft at this altitude operate at the outer edge of the outer radiation belt.

In contrast, the *safest* of all flights in space—in terms of potential impacts of high energy particles on spacecraft, equipment and spacecraft operation—are shorter missions that operate in low-Earth orbits (at altitudes of 120 to 300 miles) during years of minima in the 11-year solar cycle. An example was the historic, first flight of John Glenn, who circled the Earth, alone, in a *Project Mercury* capsule at low latitudes for six hours on the 20th day of February in 1962, well into the declining phase of solar cycle 19.

ORBITAL ALTITUDES OF SPACECRAFT IN RELATION TO PROXIMATE ATMOSPHERIC FEATURES

FEATURE / ***SPACECRAFT ORBIT***	**DISTANCE ABOVE THE EARTH'S SURFACE IN MILES**	**DISTANCE FROM CENTER OF THE EARTH IN EARTH RADII**
Bottom of F Region in Ionosphere	90	1.02
Height of Auroral Displays	170 - 360	1.04 – 1.09
Low-Earth Orbits (LEO)	*≤ 1200*	*≤ 1.3*
Space Shuttle International Space Station Hubble Space Telescope	*250*	*1.06*
Top of F Region	650	1.2
Medium Earth Orbits (MEO): GPS Transmitters	*6000 – 16,000*	*2.5 - 5*
Inner Radiation Belt	650 – 12,000	1.2 –3.0
Gap between Inner and Outer Belts	12,000 – 16,000	3 - 4
Outer Radiation Belt	16,000 – 24,000	4 – 6 or more
Geosynchronous Earth Orbits (GEO): Weather Satellites Telecommunications Satellites	*22,200*	*6.6*
Spacecraft Operating at L1 Lagrangian Point: SOHO (Sun Imaging Spacecraft) ACE (First Sentinel Spacecraft)	*930,000*	*234*

Destructive Particles From the Sun and the Earth's Radiation Belts

As with projectiles fired from a gun, the most destructive of atomic particles are the largest, heaviest and fastest moving.

Protons, which are about 2000 times heavier than electrons, are the most common ions released from solar flares and CMEs. When accelerated to speeds that approach half the velocity of light—which happens in major flares and CME-driven shocks—they are hard to stop and extremely destructive.

When an atom of hydrogen (consisting of one proton, one electron and nothing else) is ionized, its single electron is torn away from the positively-charged proton to which it was bound. Since hydrogen is far and away the most abundant element in the Sun—90% by number, 70% by weight—it is no surprise that protons comprise so large a fraction of the energetic particles thrown off from the Sun, or that they are the leading agents of disruption and damage to spacecraft and space equipment.

Heavier solar particles, including ionized helium (alpha particles) or the electron-stripped atoms of other elements, are also ejected. The *heaviest* of charge-accelerated solar particles—the cannonballs of solar projectiles—are ionized atoms of iron, which, though their speeds are not as great, can be more than fifty times heavier than protons.

Other potentially-damaging particles come from the hordes that are trapped and held in the Earth's radiation belts. Some of these came from the Sun, in the solar wind or from violent solar eruptions.

But mixed among them are an equal or greater number that entered the radiation belts not from other worlds but from our own: migrant electrons, protons and heavier ions from the ionosphere and thermosphere that diffused upward, and because of their electrical charge, were captured and held in the magnetosphere. The disturbances that set any of these charged particles free are geomagnetic storms triggered by solar eruptions or streams of high-velocity solar wind that for a brief time disrupt the bonds that held them there.

Cosmic Rays

Galactic cosmic rays are the most energetic of particles found in space. The most prevalent are high-energy protons, but as with particles from the Sun, there are also much heavier ions, ranging from the nuclei of helium atoms (atomic weight four, or four times the weight of a proton) to the relatively abundant ions of iron (weight 56). And they travel outward at speeds that can considerably exceed most particles of solar origin.

The reason for the great energies and high speeds of cosmic rays, and why they include heavy ions such as iron, nickel and zinc, is that they are propelled outward from cataclysms far more violent than any large solar flare—or a thousand of them set off all at once. The source of most cosmic rays is thought to be the explosion—long ago and far away—of an entire star, called a supernova: as though the star we live with were one day suddenly and unexpectedly blown to bits.

A cosmic catastrophe of this scale releases an almost unimaginable amount of energy all at once, propelling extremely energized electrons, protons and heavier ions at phenomenal speeds in all directions through all of space.

Because of their high energies, it is nearly impossible to shield a spacecraft, a computer, other space equipment, and any human passengers against them, since those of highest energies can pass through many inches of heavy metal. They are also nearly impossible to avoid, for cosmic rays are everywhere throughout the universe, and arrive in the solar system—but little slowed after tens of thousands of years of travel—in a cross fire of killer rays, coming from all directions.

Atmospheric Drag

Spacecraft operations are also directly affected by the two- to ten-fold increase in solar EUV and x-ray radiation in years when the Sun is more active.

When radiation in this short-wave region of the solar spectrum is absorbed by atoms of air in the thermosphere it raises the temperature there. In response, the thermosphere swells, expanding upward into regions of the more diffuse exosphere where spacecraft in low-Earth orbits fly.

This intrusion of denser air from the thermosphere increases the friction—or drag—on spacecraft that travel through it. The added drag slightly slows the space vehicle, causing it to drop to a lower altitude. There the air is even more dense, leading to a compounding effect on spacecraft altitude.

Unless the spacecraft is boosted to a higher operating altitude—at the cost of some of its limited supply of orbital control fuel—this chain of events will inexorably pull the spacecraft down into the far denser middle and lower atmosphere of the Earth, where increased friction will ultimately tear it apart.

As the thermosphere expands, the rising tide affects all boats that orbit the Earth below an altitude of about 1000 miles. The *Hubble Space Telescope* and *Space Station* are among many spacecraft that have made orbital corrections using control jets to compensate for the changing moods of the Sun: as they soon will again, as solar activity begins its climb toward a maximum of solar cycle #24 in about 2013.

These thermospheric expansions occur in response to both the year-to-year cyclic rise in solar activity and—on scales of hours to days—the intense bursts of short-wave radiation from major solar flares.

The increased atmospheric drag that accompanied the Bastille Day flare of July 14, 2000 led to the immediate demise of Japan's *Advanced Satellite for Cosmology and Astrophysics (ASCA)* by disabling its ability to maintain its orientation in space. This sent it into a catastrophic spin that led to a total loss of power, since the spacecraft could no longer keep its solar power panels directed toward the Sun.

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Skylab, the first manned space station, fell victim to the very object—the Sun—which it had been built and launched to observe, as a result of a year-by-year increase in thermospheric drag.

Carrying a battery of six of the most advanced telescopes ever pointed at the Sun, *Skylab* was lofted into low-Earth orbit in 1973, during the declining phase of solar cycle #20. Through the efforts of ground controllers and three successive teams of three astronauts—who relieved each other in space at the end of prolonged stays—the spacecraft and its crews completed its ambitious mission within eight months.

On the 8th of February 1974 the third, last and longest-staying crew turned out the lights, closed the door and returned to Earth in the space capsule that had brought the first team there. The abandoned spacecraft—as big as a boxcar and weighing about as much—was left behind to circle the Earth: a ghost ship like the *Mary Celeste*, which was found adrift in mid-ocean in 1872, fully laden and with no one on board.

In 1975, magnetic activity on the surface of the Sun began an extremely steep rise, climbing to the unusually high maximum of solar cycle #21 that was reached three years later, in 1978. The steep increase in solar activity brought an ever-increasing dose of short-wave radiation from the Sun, swelling the thermosphere and dragging the abandoned *Skylab* farther and farther down into the atmosphere: much faster than what had been anticipated.

In 1979, two years before the completion of the first *Space Shuttle*—which, had it been ready, could have been sent to boost the sinking spacecraft into a higher and safer orbit—the abandoned *Skylab* spiraled downward, out of control into the dense air of the lower atmosphere. There the most sophisticated and expensive solar observatory in the world broke apart into chunks, large and small, which fell to the ground: by good fortune over an uninhabited stretch of the Australian desert.

Impacts on Micro-Circuits and Computer Systems

High levels of electrostatic charge—created through contact with energized electrons—accumulate on the outer surface of a spacecraft as it passes through the Earth's radiation belts, during geomagnetic storms, and particularly when immersed in low-density plasma. The amount of charge deposited on the skin of the spacecraft will vary from one place or one material to another, establishing a difference in electric potential between them. This voltage difference can provoke electrical discharges—not unlike strokes of lightning—between different areas on the spacecraft, or between the different materials that are employed for thermal control.

Free electrons in space can also induce electrical charges on cable insulation and other non-conducting materials *within* the spacecraft, leading to similar and more harmful electrical discharges there. The effects can seriously damage components and subsystems, burn out power supplies and set off automatic commands in the spacecraft control system.

Highly energetic atomic particles—and most especially trapped electrons in the radiation belts—are able to penetrate the protective shell of a spacecraft and induce *deeper* electrical charges within electronic and computer components that can cause malfunctions, serious damage and even equipment failure.

In passing through the spacecraft, its computers and other equipment, high energy particles will also ionize some of the material through which they travel, leaving a trail of electrically-charged "particle tracks" across and through circuit boards and other critical components. Intruding particles that are less energetic can induce harmful surface charges on sensitive equipment. Spacecraft control systems are among those affected by either deep-charging or space-charging, leading to the possible loss of the spacecraft itself.

The thousands of spacecraft that have operated in space in the course of the last half century have provided what is now a long record of equipment malfunctions and failures, most of which are attributed to energetic electrons trapped within the magnetosphere, solar energetic particles, and cosmic rays. Such events are sufficiently common to be separated into different categories of cause or effect.

Among the classifications routinely used are electrostatic discharges (ESD) due to surface or deep dielectric charging, and several classes of single event effects (SEE) that are traceable to a single high-energy particle. Most common among the latter are single event upsets (SEU) in micro-circuits, which occur most often when a heavy ion deposits enough charge on a sensitive circuit element to cause it to change state: the equivalent of throwing a two-pole switch from OFF to ON, or ON to OFF.

Single event upsets are a common cause of disruptions and even failures in electronic equipment in space. Among the critical functions affected are the spacecraft's orbital control and stabilization system. A great many military and commercial telecommunications satellites fly in geosynchronous orbits at an altitude of about 22,200 miles above the Earth's surface, near the outer edge of the outer radiation belt, which makes all of them highly vulnerable to damage from single event upsets. The galaxy of GPS spacecraft, which operate within the outer radiation belt, are among those that have experienced many costly upsets of this kind.

Damage to Other Space Equipment

Most spacecraft are powered by solar cells, which in space—as on Earth—absorb radiative energy from the Sun in the visible and infrared regions of the spectrum and convert it into voltage, and hence available electric power. But when taken above the Earth's atmosphere, solar cells are directly exposed to a continuing barrage of high-energy atomic particles as well. These come not only from the solar wind and solar eruptions and from more distant sources as cosmic rays, but also from confined streams of highly energetic particles that circle the Earth in the two radiation belts.

High-speed atomic particles that slam into the face of solar cells are like grains of gravel thrown against the windshield of a speeding automobile, reducing their transparency and hence efficiency in converting radiant to electrical energy.

Particles from a single, moderate intensity solar event can reduce the efficiency of solar cells by about 3%, a drop sufficient to shorten the orbital lifetime of the spacecraft. CMEs and a major flare on March 13, 1989 chopped years from the designed lifetimes of more than a dozen satellites in geosynchronous orbits.

Among those affected by these events was a NOAA *GOES* weather satellite, one of two then positioned over the western and eastern halves of the continental U.S. to provide the pictures of clouds and storm systems seen daily on broadcast television. In one day these great blasts from the Sun—whose direct effects on the Earth were felt for about six *hours*—took about six *years* from the expected lifetime of the spacecraft. Two years later, in October, 1991, other large CMEs reduced the life of all three of the *GOES* spacecraft by about two years. As a result, NOAA and NASA had to accelerate the funding, building, testing and launching of replacements, years earlier than originally planned.

Incoming particles that pass through digital imaging devices, like telescopes of various kinds, can cloud and obscure the image obtained. Any charged particles can do this, including electrons and the many secondary particles that are released internally when a more energetic particle, such as a solar proton, strikes the material surrounding the detector. When a cloud of heavy ions from a solar flare or CME-driven shock wave reaches a spaceborne telescope that is pointed at the Sun, the electronic "noise" it produces can saturate the photo-sensing element. Images recorded at these times look much like the view through the windshield of an automobile driving at night in Wyoming through a blizzard of blinding snow.

Protecting Against Damage From High-Energy Particles

Before it enters the atmosphere, an accelerated electron can pass through about a quarter inch of aluminum, and a solar proton at least some six times farther, through an inch and a half or more. Thus the light-weight exterior shells of most spacecraft provide little if any shielding against either of them.

As noted earlier, for galactic cosmic rays with energies in the range of a billion electron volts (1 GeV) there is no practical brute-force method of shielding for either the spacecraft or equipment within it, given the weight of thick, denser metals like lead or steel. Thus galactic cosmic rays can shoot right through a spacecraft, from top to bottom, side to side, or end to end. Nor will they be stopped or significantly slowed by conventional materials that encase computers and other vulnerable electronic equipment.

Another limitation in using metallic shielding is that of the secondary particles that are produced when the primary high-energy particles are stopped within it. At some point, depending on the thickness of the shielding material, these secondary showers can create deleterious effects that surpass the potential damage from higher-energy primaries.

Partial engineering solutions to these problems involve the classic trade-off between insurance and its cost: in this case, between level of protection and launch weight. In practice, while it is possible to shield against less energetic particles, and to make greater use of more costly, radiation-hardened electronic components, it is prohibitively expensive to provide 100% protection of any complex spacecraft component or instrument against high-energy cosmic rays and solar protons.

Most satellites today—due to their increased complexity, greater reliance on micro-electronics, and increasing use of on-board data processing and storage—are more susceptible to the perils of space weather than those of yesteryear. The commercial use of space, in particular, calls for lower launching costs, lighter spacecraft with even less shielding, and off-the-shelf components in place of those that are radiation-hardened.

Since future spacecraft are likely to be smaller and lighter, and therefore provide less redundancy and use even more-miniaturized and complex electronic systems, they will be more vulnerable to the damaging effects of high-energy atomic particles. In addition, with more telecommunications satellites in high geosynchronous orbits and space missions of greater complexity, more spacecraft will travel into harm's way, beyond the greater safety of low Earth orbits.

With these trends we can expect more frequent single event upsets and more costly disruptions and failures in space operations.

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There are four ways of minimizing radiation hazards to spacecraft and space equipment. The first three—which in most cases prove costly or impractical—are more shielding, greater redundancy, and a more conservative choice of orbits and flight paths.

The fourth is earlier warnings of hazardous times and of specific solar and magnetospheric events. Periods of expected high (or low) solar activity can be foretold, as can the *probabilities* of solar flares, CMEs and geomagnetic storms. More useful predictions and alerts depend upon the constant surveillance of the Sun, from multiple spacecraft and vantage points. They also require advance "sentinels" like the *ACE* spacecraft, stationed slightly closer to the Sun than we, to sense and evaluate oncoming streams of plasma in the fast solar wind and CMEs in order to extend the warning times of those most likely to impinge upon the Earth.

Impacts on Telecommunications, GPS, and Navigation

The electromagnetic waves that today carry information of all kinds are everywhere and ever present in our lives: spreading not only around the world but in some cases far beyond it, through the heliosphere and throughout the Galaxy.

In but four hours, television programs broadcast to viewers in Chicago will have already reached the orbit of Neptune, and in less than a day have spread beyond the heliosphere to fill the wide open spaces where other stars abound. Electromagnetic waves carrying live television programs featuring Jack Benny, Red Skelton or Lucille Ball are at this time arriving at places more than fifty light-years away, having already passed five of the twelve brightest stars in the sky. Sirius, a near star that is the brightest of these, had its chance to watch these classic broadcasts, live from the U.S.A., more than forty years ago.

Our use of electromagnetic waves to convey information was but a century ago limited to telegraphy; for carrying voice messages from hand-cranked phones over local telephone lines; and for the transmission of code or spoken words in wireless radio messages within a limited segment of what was then called the "short-wave" radio band.

The full extent of the radio-frequency spectrum—a range of wavelengths spanning ten orders of magnitude and divided into nine frequency bands from ultra-low (3000 cycles/second) to super-high (30 billion per second)—has now been commandeered for modern needs. To meet the requirements of myriad users, the nine frequency bands are now divided and subdivided into more than a thousand separate but closely-packed segments—such as *aeronautical radio navigation*, *TV channels 7-13*, or *radio astronomy*—each allocated by international or federal commissions for a highly specific purpose.

Today, ordinary people rely on electromagnetic waves every day of every week for cell, cordless or hard-wired telephones; to receive radio and television broadcasts; for connections between computers and to the internet; and for remotely locking the car, opening the garage door or a host of other wireless applications. Electromagnetic waves are also used for an expanding list of civil, military and commercial purposes, which range from the transfer of transactions from automated teller machines and cash registers to communications of all kinds between points on land, sea, in the air, and in space.

And most of them are vulnerable in one way or another to the changing moods of the Sun.

Direct and Indirect Reception of Radio Waves

Radio waves sent outward from a broadcast TV tower or a cell-phone held in your hand spread outward in expanding circles, like ripples on a pond: but in this case in three dimensions and at the speed of light, 186,000 miles per second. Like waves in water, their advance in any direction proceeds along straight lines from the source.

This means that transmitted radio signals are unable to follow the curvature of the Earth to continue like a bird or an airplane beyond the horizon. The limit of their direct line of travel depends upon the height of the transmitter and the lay of the land, but in most instances is considerably less than 100 miles. For a person five or six feet tall standing on a flat reach of land, the horizon is less than three miles away; and for a dachshund, it is very near at hand.

Electronic signals, including broadcast radio and TV, can be sent beyond the horizon by the use of appropriately-sited relay stations and long-distance cables. And more commonly today, by re-transmission from telecommunications satellites from whose vantage point—more than 4000 miles high—the visible horizon of the Earth extends for thousands of miles in all directions.

Signals sent outward in low frequency bands of the radio spectrum—including among others, most amateur and all AM radio transmissions—are able to make it beyond the horizon without added help by forward reflection from the ionosphere: the electrically-conducting layers of free electrons and ions in the upper atmosphere that lie far below the lofty heights at which telecommunications satellites fly. Depending on its structure and density at the time, the ionosphere can for other radio frequencies serve as a polished mirror to allow them to go over the horizon and extend their range by repeated reflections far beyond it.

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It was through ionospheric reflections of this kind that in 1901, the twenty-seven year-old Guglielmo Marconi sent the first wireless signal between the Old World and the New, by successfully transmitting • • • , the three dots of the letter S in Morse code from England, "round the protuberance of the earth", to a receiver in Newfoundland, more than a thousand miles away.

Today, with adequate power and the application of very low frequencies (using wavelengths more than sixty miles long!), radio signals are bounced back and forth in the space between the Earth and the lower ionosphere all the way around the planet.

Electromagnetic signals transmitted in higher frequency bands—including the segments of the radio spectrum allocated to satellite communications, GPS, FM radio, and broadcast television—are not reflected by the ionosphere and are thus able to pass through it with little attenuation, to continue outward into space. This is why un-named, faraway planets can today receive live broadcasts of *I Love Lucy* while a viewer in the 1950s, but tens of miles from a transmitter located on the other side of a hill or down in a valley, could not.

Role of the Sun and Solar Variations

All of the telecommunications signals that pass through or are reflected by the concentrated layers of electrons in the ionosphere are affected by the Sun and solar variability, since it alone creates and sustains the ionosphere. Solar flares, CMEs, and magnetic storms—the products of solar disturbances—provoke abrupt and drastic changes in the ionosphere that can weaken, distort or temporarily block signals which under other conditions would be more cleanly reflected or allowed to pass.

The daily rotation of the Earth—carrying darkened regions of the globe into and then out of the direct blast of solar short-wave radiation—forces dramatic day-to-night changes in the density and structure of the ionosphere that exert a major impact on the range of reception of radio signals.

Day-to-day changes in the level of magnetic activity on the Sun and hence in the amount of short wave radiation received at the Earth alter the density of free electrons in the ionosphere, as do year-to-year changes in the course of the 11-year solar cycle. These solar-driven variations in electron density control not only the *reflectivity* of the ionosphere but its *transparency* and *homogeneity* as well.

Satellite communications and all others which make use of satellite repeaters rely on higher radio frequencies that are able to pass *through* the ionosphere. But these too are subject to solar-driven perturbations that not only alter its transparency to waves of different frequencies but also introduce irregularities in its structure. The radio waves that pass through a rippled region of this kind are distorted, introducing scintillations in the signal received, which are not unlike the twinkling of a star.

Among the many telecommunications systems affected by changes in ionospheric transparency and homogeneity are communications between spacecraft and the ground; marine and aircraft navigation; GPS signals; guided missile systems; and all applications, including satellite telephones and network television that rely on satellite repeaters operating well above the ionosphere in geosynchronous orbits.

Nor can the effects of the Sun on telecommunications be avoided by sending signals along wires or through under-ground or under-sea cables. These too, are affected by the Sun when CMEs and flares disturb the magnetosphere, and through this link induce troublesome electric currents in long conductors of any kind at or below the surface of the Earth

Impacts on GPS and Other Navigation Systems

The *Navstar* Global Positioning System—so extensively utilized today—relies on a fleet of twenty-four GPS spacecraft, each equipped with radio receiver-transmitters and atomic clocks. These circle the Earth at an altitude of about 16,000 miles, about three-fourths as high as the geosynchronous orbits (22,200 miles) where telecommunications satellites fly. At this height the GPS spacecraft operate in an unfriendly world, immersed in swarms of energetic electrons in the middle of the Earth's outer radiation belt.

Whether on the ground, at sea, in an aircraft or on another spacecraft, a GPS receiver can determine its own position based on the differences in the elapsed times between the transmission and reception of signals from four satellites in the GPS fleet, which utilize frequencies sufficiently high to pass through the ionosphere.

The times of travel of the GPS-to-ground signals are affected by differences in density in different regions of the ionosphere through which the four transmitted signals pass. The precision of measurement is also affected by ionospheric scintillations. While endeavors are made to compensate for at least some of these effects, transient variations in ionospheric conditions can still affect the accuracy of any GPS result. Errors of this nature are encountered about 20% of the time during the years when the Sun is most active.

Because of the altitude and the region of near-Earth space in which it must operate, the electronic equipment employed on GPS spacecraft is also highly vulnerable to deep dielectric charging and other damaging effects from high-energy particles, which are thought responsible for many single-event upsets in its operation.

The venerable *Loran* (Long Range Navigation) system that for more than sixty years was maintained by the U.S. Coast Guard to serve navigators on ships at sea, was based, like GPS, on differences between the times of receipt of radio signals from two or more different radio transmitters. For *Loran* these signals came, however, from fixed stations on land, and in order to reach distant vessels far over the horizon were carried on very low radio frequencies that reach them by repeated skips between the reflective ionosphere and the surface of the sea.

It too, was vulnerable to solar and magnetic disturbances which could abruptly alter the density and reflective properties of the ionosphere and for a time thwart attempts to use the system. Following the major solar flare of March 13, 1989, for example, the system was effectively disabled for more than four hours.

Effects on Electric Power Transmission

The delivery of electric power to densely populated areas of the United States has been severely disrupted or cut-off altogether on repeated occasions in the past following large solar disturbances and major geomagnetic storms. In several instances, the total costs of the solar-induced outages amounted to tens of millions of dollars, and in one case reached the level of financial losses encountered in the course of major floods and hurricanes. It has been shown, moreover, that space weather conditions affect the wholesale market for electricity even at times of reduced solar and geomagnetic activity.

The major disruption most often cited is the power blackout in the Province of Quebec and electrically-linked regions of the northeastern U.S. that followed the exceptionally large flare, CME and geomagnetic storm of March 13, 1989. While the 1989 power failure was unusually extensive and costly, other disruptive events of the same nature and origin had been experienced before.

Solar disturbances that tripped transformer banks, damaged equipment and disrupted electric power in wide areas had affected this country and Canada in 1940, 1958, 1972, and later in 2000. In each case they followed major magnetic storms and auroral displays in maximum years of the Sun's 11-year cycle. Similar solar conditions are next expected in the period from about 2011 to 2015.

The Power Blackout of 1989

The solar eruptions that initiated the chain of events that caused the massive power failure in March 1989 came from an extremely extensive and magnetically-complex region on the surface of Sun. This immense area—more than 40,000 miles across and roughly half as wide—contained a tangle of very strong and oppositely-charged magnetic regions, including a large collection of sunspots, some of enormous size.

To solar observers who through telescopes saw this menacing collection come around the eastern limb of the Sun, or watched the sunspots drift with solar rotation toward the center of the solar disk, it must have seemed like an approaching armada of gun-laden galleons sailing in tight formation. And indeed, in their fourteen-day passage across the face of the Sun the assembled group fired off nearly two thousand flares and lobbed at least three dozen large CMEs outward toward the planets.

The impact on the Earth of the greatest of these CME eruptions was the largest magnetic storm ever recorded, accompanied by colorful displays of the aurora borealis seen far south of their expected limits in Canada and the northern U.S.: this time reaching as far south as Southern California, Arizona and Texas and on into Mexico, Central America and the islands of the Caribbean. In Europe, where they are most often seen in the skies of northern Scandinavia, aurorae appeared as far south as Spain, Portugal and Hungary.

But the geomagnetic storm that produced these awe-inspiring sights had quite another impact on the electric power industry and its customers in Canada and the northeastern U.S. There, where the brunt of the magnetic changes were felt, it generated unwanted electrical currents at ground level that found their way into transformers and power lines, disabling generators, destroying equipment, and setting off a chain of disruption and system collapse. Hardest hit and the epicenter of damage and destruction was the Hydro-Quebec Power Company in the city of Quebec. It alone suffered losses in that one event of at least ten million dollars, and its customers lost many tens of millions more.

The same storm caused power blackouts in quite separate places in the U.S., from Maryland to California and as far south as Arizona. Among the many casualties was a massive ten million dollar transformer at a nuclear power plant in New Jersey that was damaged beyond repair.

Effects of the 1989 super storm were also felt across the ocean in Sweden, where equipment and power were also disrupted. It also touched neighboring

Finland, although there, the preventive care that had been paid to the design of circuits and system elements kept them from sustaining damage or loss.

How Magnetic Storms Disrupt Power Systems

The impact of high-speed plasma clouds from the Sun on the Earth's magnetic field greatly increases the flow of electric current in both the magnetosphere and ionosphere. And although sixty miles and more above the surface of the Earth, variations in these upper atmospheric current systems provoke rapid rates of change in the surface magnetic field of the planet, leading, in turn, to marked differences in the electric potential at different locations on the surface of the ground.

The electric potential of the Earth's surface at places ten miles apart can differ by as much as 160 volts. In time these inequalities will be gradually drained away by a leakage of sub-surface electric currents passing through the weakly-conducting ground. But when grounded wires, sub-surface cables, pipelines, iron railroad tracks or other metallic conductors happen to connect regions of different surface potential together a short circuit ensues, much as when a metallic object is inadvertently placed across the poles of a storage battery. The sudden direct currents that instantly flow through these shunts of opportunity—typically 10s to 100s of amperes—are known as geomagnetically-induced currents or GICs.

When a direct current of this kind, passing (in the wrong direction!) *up* a ground wire reaches the windings of a high voltage transformer at generating plants or substations it initiates a chain of disruption. This includes transformer saturation, overheating and other damaging effects that can ultimately trigger protective relays throughout the system to which it is connected.

In extreme cases the effect can ripple through an entire electric power grid, leading to a possible collapse of the network, pervasive power blackouts, and permanent damage to the immense transformers and other large and seldom-ordered components, like large transformers, that are both very costly and very slow to replace since they are individually manufactured on demand.

Where Solar-Driven Power Outages Most Often Occur

Damaging GICs occur predominantly in higher-latitude regions where the most violent magnetic disturbances occur and aurorae are most frequently seen. In the U.S. they are most prevalent along the top two tiers of the connected forty-eight states. In addition within the upper tier, the eastern half of the U.S. is more likely to be hard hit by the effects of GICs than states west of the Mississippi. This inequity stems from geological differences in the conductivity of the subsoil in the two regions, which is more rocky in the Northeast and hence more resistant to the flow of equalizing sub-surface electric currents; and also from differences in population density.

North America, moreover, is more prone to damaging GICs than is northern Europe or Asia, because of the present, western offset of the north magnetic pole, that allows more incoming charged particles into the top of the western world than at equivalent geographic latitudes in northern Europe and Asia.

Thus it is not by chance that so many of the severe solar-induced power disruptions in the last sixty years have struck the eastern provinces of Canada, and in this country, large metropolitan areas in the Northeast and North central states. This is not to say that other regions are by geography immune. The severe magnetic storm of August 4, 1972, for example, had direct impacts in British Columbia and down into the U.S. Midwest.

Today the major determinant of where power blackouts will occur in our country is not so much the present skewed location of the north magnetic pole or the resistivity of the soil in rocky New England, but the extent of interconnected electric power systems. With these much expanded grids—which now connect high-prone Northeastern power plants and distribution systems all the way to the Gulf States—no city is an island.

A magnetic storm as intense as the one that caused so much damage in the Hydro-Quebec power system in 1989 would today affect a far larger area. In this not-unlikely event, two vast sections of the U.S. would likely suffer a total power system collapse, requiring days to bring the entire system back on line.

The first and largest of these would likely encompass most of the eastern states, in an area reaching from Maine to northern Florida and extending westward as far as St. Louis, Memphis and Birmingham. The second would include all of Washington, Oregon and Idaho and parts of far-northern California and Nevada. The probable cost to power companies alone of this one super event has been estimated to be at least five billion dollars: a figure which would be dwarfed by the total economic losses in the communities involved and throughout the nation.

SOME MAJOR ELECTRIC POWER DISRUPTIONS IN THE U.S. AND CANADA TRIGGERED BY SEVERE GEOMAGNETIC STORMS

STORM DATE	AFFECTED AREA
1940 March 24	Eastern Canada, Central and Northeastern U.S.
1958 February 10-11	Eastern Canada, U.S. Upper Midwest
1972 August 4	Western Canada, U.S. Upper Midwest
1989 March 13	Southern Canada, Northern U.S.
2000 July 14	North America
2003 October 29-30	Northeastern U.S.

Effects of Geomagnetically-induced Currents on the Cost of Electricity

Geomagnetically-induced currents provoked by solar activity and geomagnetic storms can affect the price of electricity, regardless of the magnitude of the disturbance, through a reduction in the ability of electric power distribution systems to deliver low-cost power to areas of higher demand.

A recent study of a major Northeastern power grid serving almost 10% of the population of this country found that the cost of GIC losses to consumers amounted to about half a billion dollars in the 18-month period that was examined. The price impact was not surprisingly a strong function of the severity of the geomagnetic storm, but less intense storms also took their toll. Following a major storm like that triggered by the Bastille Day flare and CMEs of July 14, 2000 the wholesale price of electricity was more than doubled, and the average over all geomagnetic disturbances, large or small, was a not-insignificant increase of 3.3%.

Early Signs of Solar Interference in Communications

Pipelines and cables—whether on, above, or beneath the surface, or laid across the ocean floor—can also be affected by geomagnetically-induced currents. These too, are electrical conductors in a position to provide a short-circuit path between separated surface areas of different electric potential.

In 1926, at a time when far more was known about sunspots than about geomagnetically-induced currents, Guglielmo Marconi—then fifty-two and still much involved in telecommunications—called attention to the fact that the times when undersea cables and land-lines were thrown out of action seemed always to coincide with the appearance of large sunspots and intense aurorae. And that these were also times of frequent fading of high-frequency wireless radio transmissions.

The occasional presence of "anomalous currents" in telegraph wires had been commented upon as early as 1847, although at that time neither geomagnetically-induced currents nor their solar and magnetospheric causes were known or understood. Nor was it probably noted that 1847 marked the peak of the 11-year solar cycle (cycle #9) that ran between minima in 1843 and 1856.In fact, at that early date very few people anywhere were aware of the Sun's cyclic behavior, even though Heinrich Schwabe had published his landmark paper announcing that finding four years earlier, in 1843 in the scientific journal *Astronomische Nachrichten*.

But few had read it at the time and fewer still were prepared to accept what he claimed as fact. Schwabe's Cinderella paper would have to wait four years more, until 1852, when Doktor Professor Alexander von Humboldt— not an amateur like Schwabe, but a celebrated professional scientist of world renown—endorsed the pharmacist's discovery by calling attention to it in his four-volume series of widely-read popular books, entitled *Cosmos: A Description of the Universe*. Then as now, for Schwabe (whose life was suddenly changed) it was not so much what you knew, but whom you knew.

Some Effects of GICS on Telecommunications Cables

Following the severe magnetic storm of February 11, 1958, telephone and teletype signals carried in the first-ever transatlantic telecommunications cable—running between the shores of Newfoundland and Scotland—were disrupted for almost three hours due to the excessive geomagnetically-induced currents that were imposed. Telegraphic messages were garbled, and words politely spoken at one end of the line were heard at the other as squeaks and whistles: like sounds from a flock of starlings.

Geomagnetically-induced currents caused by the great solar flares of early August, 1972—and by unseen CMEs which at that time had yet to be discovered—succeeded in disabling an AT&T telecommunications cable that ran from Chicago to the west coast. One of the effects was to cut off all long-distance telephone traffic between Chicago and Nebraska.

Since 1990, four out of five transoceanic telephone calls are carried in cables beneath the ocean. During the record-breaking magnetic storm of March 14, 1989, the first-laid transatlantic voice cable running along the ocean floor was rendered almost inoperable when large electric currents were induced in it by the storm-induced difference in electrical potential between the cable's terminal stations in New Jersey and England. Nor has the switch to wider-bandwidth optical fiber cabling made much of difference in this regard, since the bundles of glass fibers are bound with conducting wire. These too, pick up and transmit unwanted electrical currents at times of severe magnetic storms.

Damage to Pipelines

Geomagnetically-induced currents can also accelerate corrosion in metal pipelines, such as those used to carry oil or natural gas over distances of hundreds to thousands of miles. The intrusion of magnetically-induced currents can also interfere with the technical systems that are employed in pipelines to combat corrosion.

Particularly susceptible to induced pipeline corrosion are any diversions or irregularities: including places of departure from straight-line runs—such as bends and branch points—and joints where different metals meet.

Impacts of Geomagnetic Storms on Geological Surveys and Explorations

The onset of a geomagnetic storm, although playing out a thousand miles and more above our heads, is immediately registered as an abrupt change in the magnetic field at the surface of the Earth. There it is readily apparent as erratic behavior in compass needles, and readily captured for later study by continually-running magnetometers at magnetic observatories around the world.

We usually think of magnetic compasses as hand-held direction finders used by Boy Scouts and other hikers, on collapsible tripods by road-side surveyors, or freely supported in brass binnacles bolted to the deck on the bridges of ships at sea. Magnetic storms can perturb all of these familiar uses and in addition—often at great cost—the more sophisticated and automated applications in which the Earth's magnetic field is relied upon as a fixed directional reference.

One of these applications is in guiding the downward course of rotating bits used in drilling oil wells. Here any perturbation in the reference direction results in an immediate change in the direction of travel of the drill bit, which can lead to costly errors and equipment damage. Thus to drillers and surveyors a major magnetic storm is no less and probably more of a threat than the sudden onset of severe weather.

This was the case for a number of North Sea oil companies when the severe magnetic storms that followed the very large CMEs and solar flares of early March, 1989 forced them to abandon all efforts to drill.

The same event displaced compass needles for a time by a whopping 10° from the direction of magnetic north, with effects on navigators and surveyors around the world.