J1.2 WHERE AND WHY DOES SPACE WEATHER OCCUR?

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1. INTRODUCTION

Modern aviators operate in a terrestrial atmosphere, about which much is known. Despite this knowledge, some flights divert because of bad weather. On a seasonal basis, airport ramps full of aircraft are evacuated from a hurricane's paths. Terrestrial weather is monitored twenty-four hours a day, seven days a week. But what about the space environment, home to critical technology systems and billions of dollars in space assets? Who monitors it? What should space professionals know about it? What actions are taken to mitigate its effects?

This paper provides a brief survey of the primary agents and phenomena in space weather and space environment systems. It also introduces the basic terminologies undergraduate students would encounter in the first week of a space weather course. We start at the galactic level and work our way to Earth's surface. We develop a framework that enables us to discuss space weather effects.

2. SPACE IS NOT EMPTY!

2.1 Space is Not Benign

Effects of the space environment are generally beyond sight and touch. These effects occur in the realms of radio communication, spacecraft operations, high-altitude flight, extended power grids, and even computer microchip manufacturing. A significant part of civil and military operations now rely on the "good" behavior of the natural space environment. When the environment turns hostile, space operators need to know.

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Present and future aerospace leaders need space-weather awareness and knowledge of potential impacts. The following vignette illustrates space-weather effects on today's civil and military operations.

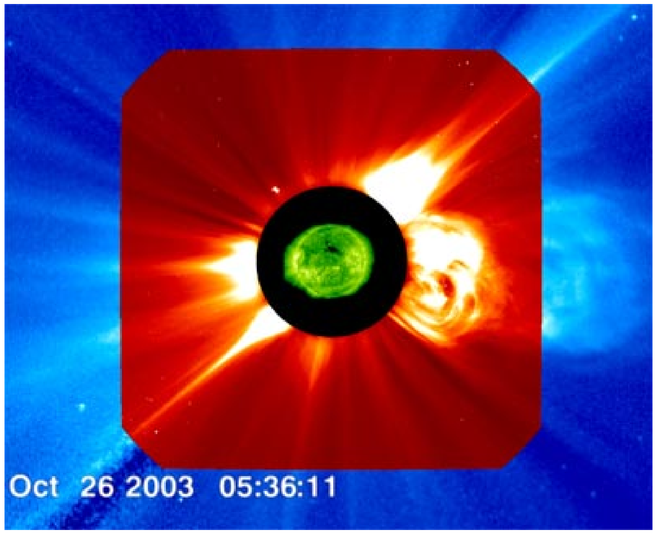
Space Weather Vignette 2003

Immediate Effects. In late October 2003 when firestorms raged along the southern California coast, weary firefighters looked at the smoke-filtered Sun to see the origins of a storm of a different sort--a solar storm. Within minutes, energetic-particle levels were so high that NASA officials directed International Space Station astronauts to take precautionary shelter. Airlines rerouted polar flights to avoid the high radiation levels and communication blackout areas. Rerouted flights cost airlines $10,000 to $100,000 per flight. From a tangled mass of magnetic field, the Sun hurled a cannonball of plasma earthward. Figure 2.1 shows one of a series of the outward propagating disturbances in the interplanetary medium.

Short-term Effects. Less than 24 hours after the fury on the Sun, utility companies reported storm-induced currents over Northern Europe resulting in transformer problems and a subsequent regional blackout. On October 28, the density of free electrons in the ionosphere on Earth's sunlit side jumped by 25%. High-frequency radio communication was disrupted. Climbers on Mount Everest could not signal base-operations. Satellite navigation was compromised in some areas. Auroras were visible in Houston, Texas, one of the more southern cities in the United States.

Long-term and Ongoing Effects. One month later the same solar-active region sent another blast toward Earth. Students at a western US college, who were finishing a precision-mapping project in a geography course, found that satellite-derived position errors went from 5 meters to 75 meters in just a few minutes. Over subsequent months, electric utility operators in the southern hemisphere discovered serious damage deep inside of power transformers. The cost to repair: Tens of millions of dollars. Space was not benign!

Figure 2.1. Mass and Energy Flowing from the Sun as Viewed by Three Instruments on the Solar Heliosphereic Observatory Spacecraft. The scope of the image is ~ 16 solar radii in the horizontal. A mask covers the bright solar atmosphere out to a distance of one solar radius. To the right is evidence of a mass ejection. The mass outflow associated with this event was roughly equal to the mass of an average mountain on Earth. This was one of a series of events associated with the vignette discussed above. (Courtesy of NASA)



2.2 Defining Space Weather

Once generally viewed as a subset of astronomy or perhaps astronautics, day-to-day interactions between Earth and the constituents of interplanetary space are now commonly referred to as ***space weather*** or ***space environment interactions.*** The science behind these endeavors is ***space physics***. ***Space weather*** describes the conditions in space that affect space-based and ground-based technology systems as well as Earth and its inhabitants. It is a consequence of the behavior of the Sun and other stars, as well as the nature of Earth's magnetic field and atmosphere, and our location in the solar system. As a practical matter, space weather often means a disturbed situation, whereas space environment usually refers to normal or background conditions. Space weather is created by electromagnetic energy from the Sun and by the Sun's out-flowing atmosphere that streams by Earth (and all planets) at tremendous speeds. Earth's magnetic field and upper atmosphere dissipate, store, and redirect some of this energy. The vast majority of energy and mass involved in space weather is from the Sun, but distant stars and closer objects, such as meteoroids, play a role too.

2.3 Places and States of Space Weather and Space Environment

The material of space comes in several states: solid, liquid, gas, and plasma. The latter state, one in which a gas is so energized that its electrons and ions have separated, dominates space interactions. A very thin soup of plasma and energy constrains and interacts with near-Earth space creating space climate, space weather, and space storms. Modeling this plasma environment remains a challenge.

What constitutes the near-Earth space environment? For practical purposes we define the region of space within 200 Earth radii (200 R_E = 1.28 x 10^6 km) as "near" Earth. By Earth standards, this is a huge volume in which over 8 million Earths would fit, but by solar system standards, this volume is rather inconsequential. We often call this region simply the space environment. Does this mean Earth's atmosphere is part of the space environment? Most definitely it is, but for the most part, we confine our discussions to atmospheric interactions occurring above 50 km. We leave the atmosphere below that level (99.9% of atmospheric mass) in the capable hands of meteorologists. However, circumstances exist in which space weather processes spawn impacts in the lower atmosphere and, occasionally, all the way to the surface. So, when necessary, we claim even the lower atmosphere as space weather territory.

The Sun is a huge, dense swirl of plasma, held together by its own gravitation. It radiates away its excess thermonuclear energy as rivers of photons, neutrinos, and charged particles. The charged particles then form a dilute plasma that sweeps through interplanetary space. Thus, an understanding of the environment of space hinges on understanding plasmas. Plasma is usually defined as an electrically neutral, ionized gas.

Although the particles in plasma have electric charges, the plasma at the macroscopic level remains electrically neutral, because the ions and free electrons, though not formally bound to each other, exist in a common hot "soup." The electrons repel each other, and the ions also repel each other. The electrons are attracted to the ions, but the electrons are usually traveling so fast they don't recombine with ions. Electrons normally travel faster than the ions because the thermal energy moves their smaller masses more readily.

Such a complex set of interactions makes plasma very dynamic. If plasma cools, the electrons slow and may recombine with positive ions to form a gas. On a macroscopic scale, plasma is very fluid, much like a gas. However, unlike a gas, plasma exhibits one property that cooler forms of matter rarely exhibit: it strongly interacts with electromagnetic fields. This property sets plasma apart. Additionally, the collective motions of charged particles generate magnetic fields that, in turn, govern the charged particle motions. In the presence of magnetic fields, individual charged particles follow magnetically bent paths as they bounce between collisions.

Newton's Second Law, $\Sigma \boldsymbol{F} = \Sigma m\boldsymbol{a}$, applies to individual particles and to collections of particles. In our everyday lives we tend to be more aware of forces acting on uncharged bodies, for example the sum of gravity and lift, $\Sigma \boldsymbol{F} = -m\boldsymbol{g} + \boldsymbol{L}$, that allows aircraft to stay aloft. In space weather applications, we often ignore gravity because its influence is small; however we consider other forces acting on charged particles, individually or collectively. Here we provide applications of Newton's Second Law of Motion for charged-particle and plasma behavior. The ***Coulomb force*** for charged particles is

$$\boldsymbol{F}_c = q\mathbf{E} \qquad (1.1)$$

Where

$\boldsymbol{F}_c$ = Coulomb force vector [N]
q = charge on a particle [C],
$\boldsymbol{E}$,= electric field vector [V/m].

This force accelerates charged particles along electric field lines. That is, $\Sigma \boldsymbol{F} = \Sigma m\boldsymbol{a} = q\boldsymbol{E}$.

If a magnetic field, $\boldsymbol{B}$, rather than an electric field, is present and the charged particle is moving, then we describe the force on a charged particle as the ***Lorentz force***:

$$\boldsymbol{F}_L = q(\boldsymbol{v} \times \boldsymbol{B}) \qquad (1.2)$$

Where

$\boldsymbol{F}_L$ = Lorentz force vector [N]
$\boldsymbol{v}$ = particle's velocity vector [m/s]
$\boldsymbol{B}$ = magnetic induction vector [T].

By virtue of the cross product, this force acts perpendicular to $\boldsymbol{v}$ and $\boldsymbol{B}$ and creates a centripetal (toward the center) acceleration**.** This force is only active when particles are in motion. In the space environment we often find both fields acting on charged particles, creating what we call the ***generalized Lorentz force***:

$$\boldsymbol{F}_L = q\boldsymbol{E} + q\boldsymbol{v} \times \boldsymbol{B} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \qquad (1.3)$$

Where $\boldsymbol{F}_L$ is now the generalized Lorentz force vector on a charged particle created by $\boldsymbol{E}$ and $\boldsymbol{B}$ fields.

The resultant motion for the charged particles is a circular or spiral path, as shown in Figure 2.1, depending on the orientation of $\boldsymbol{B}$ and $\boldsymbol{E}$.

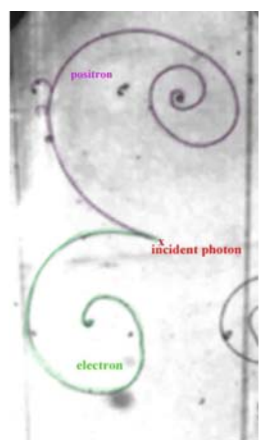


Figure 2.1. Helical Tracks of Two Charged Particles. Here we show an electron and positron, created from the decay of an energetic photon. Their motions are in the presence of a magnetic field. (Courtesy of European Organization for Nuclear Research [CERN])

Net forces cause change in velocity, which is really another way of saying that momentum is changed. Throughout discussion of space weather, we will be interested in the causes of changes in momentum, energy and mass in the space environment system resulting from space weather events.

3. SPACE WEATHER AGENTS

3.1 Other Stars Create Space Weather

Stars other than our Sun are so distant that it is hard to imagine they could have an influence on Earth's near-space environment. However, violent supernova explosions (stellar death) in our own galaxy and in distant galaxies accelerate material to near the speed of light. During such events, millions to billions of volts of electrical energy are suddenly freed. In the tumult, electrons are stripped from their parent atoms. The remaining heavy nuclei travel for millions of years through interstellar space. These nucleonic remnants of distant and violent stellar explosions, known as ***galactic cosmic rays***, arrive at Earth from all directions with extreme energies. Because of their high energy, they penetrate through large amounts of shielding material. Thus, they are dangerous to humans and equipment in space.

Cosmic rays are strongest during solar minimum when the heliospheric magnetic field provides the least shielding. These particles speed through spacecraft, the atmosphere, and the otherwise significant protection provided by Earth and interplanetary magnetic fields. Because these particles are so energetic, they penetrate well into the lowest levels of the ionosphere, where they often change radio signal propagation and the effectiveness of some radar systems. Numerous spacecraft malfunctions have been associated with these ever-present particles.

On rare occasions, violent gamma and X-ray upheavals on other stars have disturbed Earth's upper atmosphere to the point that radio-wave propagation on Earth's night side was impacted. Scientists have named the source of these impulsive stellar bursts, ***magnetars***. In March 1979, widely separated Russian and US spacecraft detectors were blitzed by a front of energy moving through the solar system. Radiation counts rose from 100 per second to 200,000 per second. Nearly 20 years later, a satisfactory explanation was finally formulated: the spacecraft had been hit by bursts of energy from a neutron star from the Large Magellanic Cloud, a sister galaxy to our own Milky Way (Kouveliotou et al., 2003). At Earth's surface, humans remained blissfully unaware. Our atmosphere had protected us. It also protects us from particle outbursts of our own star, the Sun, which tend to occur during the active phase of the solar magnetic cycle.

3.2 The Sun Creates Space Weather

The Nature of the Sun and Solar Dynamics

The Sun is a nuclear furnace that, each second, converts millions of tons of hydrogen to helium in the solar core. In the process, a tiny fraction of the mass belonging to the hydrogen atoms disappears only to reappear as energy. The reservoir of energy creates temperature gradients that force an outward-directed flow of energy. If the energy flowed out of the Sun without further interaction with matter, we could end this book here. However, the high energy photons created with each nuclear reaction are captured by matter, emitted, and recaptured and reemitted billions of times on their path out of the Sun. With each capture, they give a bit of energy to their surroundings. By the time the photons reach the solar surface, most of them have degraded to the lower energy photons that we sense as yellow visible light. The visible light is only a small part of the total energy radiated from the 5800 K surface of the Sun.

Unlike Earth, the Sun does not rotate as a solid body. Rather, the Sun rotates fastest at the equator (~25 Earth days per rotation) and slowest toward the poles (over 32 Earth days per rotation). This process is ***differential rotation*** and is one of the fundamental drivers of space weather. Further, the outer layers of the Sun's fluid interior convect (boil) similar to water in a pot. The solar plasma motions twist and wind the Sun's magnetic field into "islands" –known as sunspots, whose field strength is hundreds or even thousands of times stronger than Earth's magnetic field. Thus, ***sunspots*** are compact storage zones for the Sun's magnetic energy. Sunspots usually appear in groups and are part of a large magnetic structure known as an ***active region*** that often extends through the entire solar atmosphere. The differential twisting of the solar plasma causes relative motion of one sunspot with respect to a neighboring sunspot and sets the stage for explosive releases of energy.

Observations of sunspots over many years revealed that the numbers of sunspots change periodically. In some years as many as 250 sunspots are observed per day, in other years, none. This phenomenon is called the ***sunspot cycle*** and we illustrate it in Figure 3.1. The plot shows that the number of sunspots varies with an average period of about 11.4 years. Some cycles are as short as 8 years, others as long as 15. A period of no or few observed sunspots is called a ***sunspot minimum***. Conversely, a period of maximum number of sunspots is a ***sunspot maximum***. Beginning with the minimum that occurred around 1755, sunspot cycles have been numbered. The cycle with its maximum in 2000 was cycle number 23.

The Sun has a variety of ways to release energy. Because of the huge number of interaction between energy and solar matter, we see a relatively quiet background of electromagnetic radiation released across a broad range of wavelengths called the ***solar spectrum***. Each square meter of the top of the Earth's atmosphere receives 1366 Watts of power from the Sun. This value is the ***solar constant***, which ultimately powers our atmosphere. We also see a quiet background outflow of tenuous and highly-ionized plasma (100,000 K) called the ***solar wind***. On average, the solar wind blows past Earth at a tremendous speed of ~ 400 km/s (about 1,000,000 mph in Earth's vicinity), which is about ten times faster than the speed of sound in the rarified plasma. This directed, or ram, flow of the solar wind has kinetic energy. The random, omni-directional motion of the 100,000 K plasma particles is called thermal energy. Thermal energy is really just a form of non-directed, kinetic energy of the individual particles. Physicists associate this phenomenon with the ***temperature*** of the solar wind.

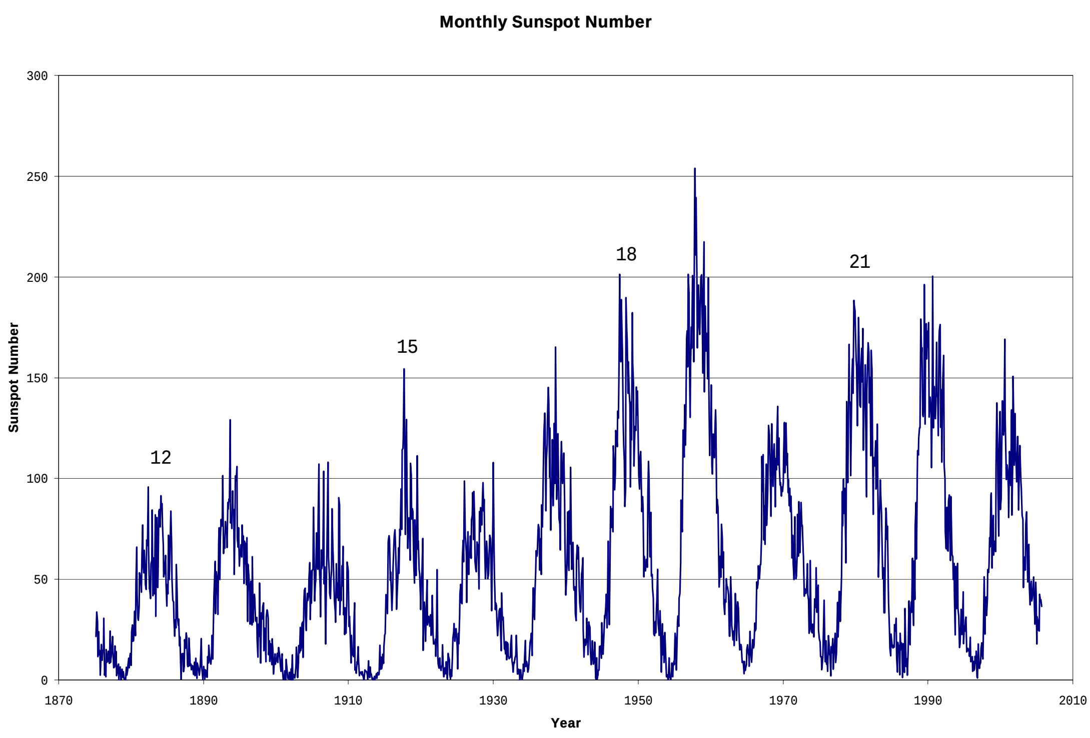


Figure 3.1. Sunspot numbers corresponding for the last 12 cycles. Selected cycle numbers are shown at the top. Data provided by the National Geophysical Data Center.

The solar wind consists of particles, mostly ionized atoms of hydrogen and helium and traces of oxygen, carbon, iron, and other elements. The radially flowing solar wind carries and stretches the Sun's magnetic field into space. In its stretched form, the solar field is the ***interplanetary magnetic field*** (***IMF)***. However, one of the ends of these field lines stays rooted in the Sun. Thus, as the Sun rotates (recall the mean rotation period is 27 days), the IMF gets wrapped into a spiral, similar to a stream of water from a rotating sprinkler. The Sun's magnetic field arrives at Earth with an angle of about 45°.

In the vicinity of Earth (1 Astronomical Unit [AU] from the Sun), each cubic meter of space typically contains 5 x 10^6 positive ions and an equal number of free electrons. This is a very low particle content compared to the 10^{25} molecules in each cubic meter of air at sea level. Variations in the Sun's magnetic field are carried outward by the solar wind and produce disturbances in the near-Earth environment called geomagnetic storms. Storms also accompany prolonged gusts of enhanced flow in the solar wind, called ***high-speed streams***. Researchers now know that the Sun emits impulsive, transient bursts of particles and energy, as well as recurrent streams of fast flow. Occasionally the mass ejections and high-speed streams merge to create a particularly potent storm.

In addition to the background energy releases, we see forms of explosive energy release that create large space weather disturbances. Most of these disturbances occur when energy stored in solar magnetic fields converts to other forms.

- ***Solar flares***—intense bursts of radiative energy across the entire electromagnetic spectrum, with the largest burst enhancements in the X-ray, extreme ultraviolet (EUV), and radio portions of the spectrum.
- ***Solar energetic particles (SEP)***—kinetic energy in the form of protons ejected with relativistic speeds near the flare site, or particles accelerated by a shock from the explosion site pushing into the solar wind.
- ***Coronal mass ejections (CME)***—additional kinetic energy in the form of huge parcels of the Sun's atmosphere accelerated (or ejected) into interplanetary space. The parcels carry threads of the Sun's magnetic field into space as well. Much of the ejected plasma is from the Sun's upper atmosphere, or corona.

Table 1.1 shows an impact grid for the important forms of the Sun's emissions. Even "quiet Sun" emissions produce geomagnetic storms.

Table 1.2 provides distances of interest in the space environment.

Table 1.1. Simplified Classifications of Space Weather Storm Effects.
Here we list various forms of the Sun's emissions and their characteristics.

Quiet Sun Emissions	Time to Arrive at Earth	Storm Impact
Photons from ~5800 K Surface	*8 min*	*Normal Conditions*
No Solar Energetic Particles	*--*	*Normal Conditions*
Solar Wind Plasma	*100 hr*	*Normal Conditions*
-- With Strong Magnetic Field	*60-100 hr*	*Geomagnetic Storm*
-- With High Speed	*30 hr*	*Geomagnetic Storm*
Disturbed Solar Emissions	**Time to Arrive at Earth**	**Storm Impact**
Solar Flare Photons (X-ray-radio)	*8 min*	*Radio Blackout*
Burst of Solar Energetic Particles	*15 min – Several hr*	*Radiation Storm*
Coronal Mass Ejection	*20-120 hr*	*Geomagnetic Storm*

The Solar Environment

Because the Sun is so close, we are able to study its behavior in detail. We are also benefactors (or victims) of its output. In our galaxy, the Sun is a middle-aged, yellow star, located about 150 million kilometers [1 AU] away from Earth—about 8.3 light-minutes away. We rarely think of the Sun as an entity with an extended atmosphere, but it has one, and it is large indeed, extending well beyond Pluto's orbit to a distance of 120-150 AU.

Table 1.2. Some Distances in Space and the Space Environment.
This table lists various distances from the Sun and from Earth.

Sun-centered	Earth-centered
Distance to galactic center	Distance to solar wind monitor*
2.47×10^{20} m = 1.65×10^{9} AU	1.50×10^{9} m = 2.35×10^{2} R_e
Distance to nearest star	Distance to the Moon
4.02×10^{16} m = 2.68×10^{5} AU	3.84×10^{8} m = 6.03×10^{1} R_e
Distance to heliopause*	Distance to bowshock*
2.3×10^{13} m = 1.53×10^{2} AU	~9.60×10^{7} m= 1.50×10^{1} R_e
Sun-Pluto distance	Distance to dayside magnetopause*
5.91×10^{12} m = 3.94×10^{1} AU	~6.37×10^{7} m = 1.00×10^{1} R_e
Sun-Earth distance	Distance to geosynchronous orbit
1.50×10^{11} m = 1 AU	4.20×10^{7} m = 6.6 R_e
Solar radius	Earth radius
6.96×10^{8} m = 4.64×10^{-3} AU	6.37×10^{6} m = 1 R_e

*terms to be defined later in the paper

FOCUS ON: The Size of Things in the Solar System

Most textbooks provide a drawing of the Sun and its planetary system that is not to scale. To give you a sense of the scaling of our solar system, consider the Sun to be the size of a 0.30 m (12 in) pie plate, which is also the approximate size of an adult foot. If you were to put the plate down and march about 110 "feet" beyond it you would reach Earth's orbit at one AU. (Try this if your classroom is in a long building which has 12 in floor tiles.) In diameter, Earth is less than 1/100th the size of the Sun, typically the size of a pencil eraser in this scheme. To give you more perspective on the relative sizes of these bodies, it is useful to note that the entire Earth-Moon system would fit inside the radius of the Sun. Now that you know the Sun is large and distant, why does it matter? Because the disturbances that arise at the Sun's surface and in its atmosphere are huge in comparison to Earth, if one of the disturbances interacts with Earth, it is likely to have spectacular and damaging results.

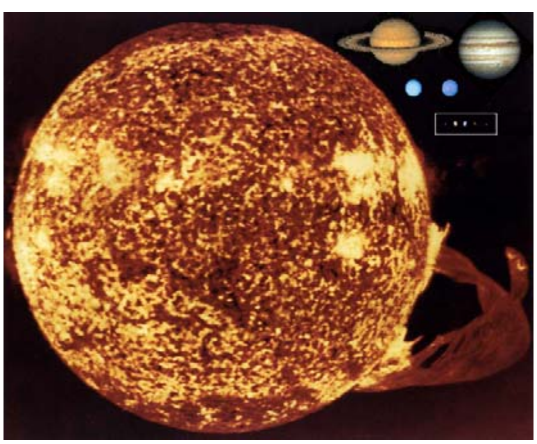


Figure 3.2. Relative sizes of the Sun and planets. (Image courtesy of N. Strobel, www.astronomynotes.com)

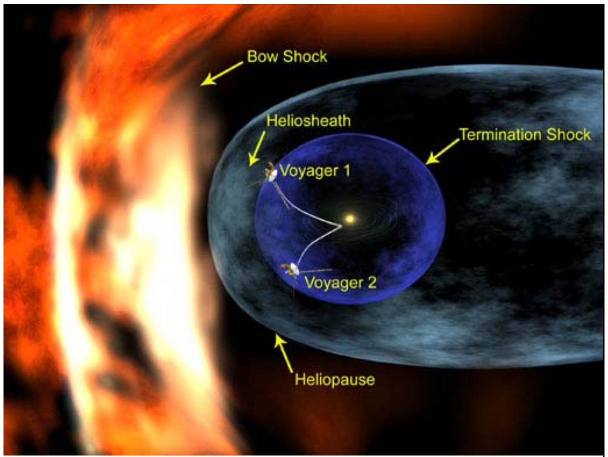
To put our entire solar system into perspective, we could scale the Sun to be the size of a large marble (about 2.5 cm in diameter). If we place our scaled Sun in Denver, Colorado, then the nearest star, Proxima Centauri, would be located in Chicago, Illinois. Alternatively, if we placed the scaled Sun in London, United Kingdom, then Proxima Centauri would be near Rome, Italy.

Heliosphere: The Extended Solar Atmosphere

The ***heliosphere*** is that region of space dominated by the Sun's extended atmosphere. It is essentially a bubble in interstellar space produced by the solar wind (Figure 3.3). The distance to Pluto is about one third the distance to the near edge of the heliospheric boundary. The bubble forms because the Sun's extended atmosphere is permeated by a magnetic field that is roughly in the form of a dipole. When a magnetic dipole is immersed in flowing plasma from an outside source, in this case the interstellar medium, it deforms into a tear-drop shape as in Figure 3.3. The outer surface where the heliosphere meets the interstellar medium is the ***heliopause***. Here the term "pause" indicates a break or discontinuity. The location of the discontinuity in solar plasma and magnetic field depends on the phase of the solar cycle. When the Sun is more active the boundary is further from the Sun because of the higher pressure generated by solar activity. In 2004, twenty-seven years after launch, the Voyager I spacecraft crossed the heliopause into the interstellar wind, at ~94 AU.

Outer Heliosphere We just introduced the idea of solar envelope, now we discuss two general regions within this envelope. Although electrically neutral atoms from interstellar space can penetrate this bubble, virtually all of the material in the heliosphere emanates from the Sun. At some distance from the Sun (well beyond the orbit of Pluto), the supersonic solar wind slows to meet the gases in the interstellar medium. At such a location, the solar wind goes through a ***termination shock*** to become subsonic. In doing so, it slows and deflects in the direction of the interstellar flow to form a comet-like tail beyond the Sun. Voyager I was in the vicinity of the termination shock in late 2004. The termination shock, where solar magnetic fields bunch, appears to be a region capable of accelerating newly ionized oxygen and helium into cosmic rays. Thus, it becomes a region of interest for those whose systems are vulnerable to cosmic rays.

Inner Heliosphere In the interior heliosphere, all planets behave as obstacles to the supersonic solar wind. A perturbation wave, or ***bowshock*,** forms upstream of each planet as a means of slowing and diverting the solar wind around the planet. Smaller solar system bodies such as moons and asteroids generally don't have bowshocks. For a bowshock to form, the body must have a magnetosphere, an ionosphere, an atmosphere, or some combination thereof. Most moons and asteroids don't qualify because they are too small to create or retain such spheres.



A

B

Figure 3.3. Heliospheres. A) An artist's rendition of the heliosphere beyond the near-space environment. The small inner yellow is the Sun. B) This image is a Hubble Telescope view of the

Bubble Nebula, a distant stellar system with its heliosphere and a stellar wind in excess of 2000 km/s. (A)Courtesy of NASA. B) Courtesy of Space Telescope Institute).

Earth's bowshock forms ~15 R_E upstream from Earth. Scientists have had a long-standing goal of positioning a spacecraft upwind of the bowshock so that incoming solar wind could be monitored for analysis and forecasting purposes. The Advanced Composition Explorer (***ACE***) spacecraft has been about 230 R_E upstream of Earth since 1997.

3.3 The Earth's Magnetosphere Results From and Contributes to Space Weather

In this section we describe Earth's magnetosphere as similar to that of the heliosphere. This similarity is not an accident. Magnetic fields immersed in moving, conducting fluids exhibit self-similar behavior over many scales.

Regions of the Magnetosphere

Earth's magnetic field would resemble a magnetic dipole at large distances from Earth, if the solar wind didn't distort it into a bullet-shaped magnetosphere (Figure 3.4). Field lines distant from Earth become increasingly stretched into a ***magnetotail*** that extends well beyond lunar orbit (60 R_E). The distortion occurs because of field line, current, and plasma interactions. As we show in Chapter 8 an adequate description of the magnetosphere must include these interactions.

Outer Magnetosphere Now we bring our tour closer to home. Just Earthward of the bowshock is a zone of disordered solar wind created by the turbulent braking of solar wind flow (Figure 3.5). In this region, called the ***magnetosheath***, flow energy converts into turbulent eddies and ultimately into random thermal motion of the solar wind constituents. Closer to Earth, the boundary separating the frothy and weakly magnetized solar wind from Earth's magnetic domain is called the ***magnetopause***. This is the surface where the magnetosphere meets the interplanetary medium. The boundary is a fluid and magnetic membrane that flexes in the dynamic solar wind. Generally the magnetopause is located at ~10 R_E. Inside the magnetopause is that region of the space environment dominated by Earth's magnetic field; the ***magnetosphere*****.** The local magnetospheric structure mirrors the structure of the heliosphere-heliopause system. This similarity is no accident. Systems with differing plasma and magnetic characteristics attempt to maintain their own identity. They do so by forming boundaries made of flowing charged particles (currents). If one system of magnetized plasma flows against another, the boundary often takes on a bullet or tear-drop shape.

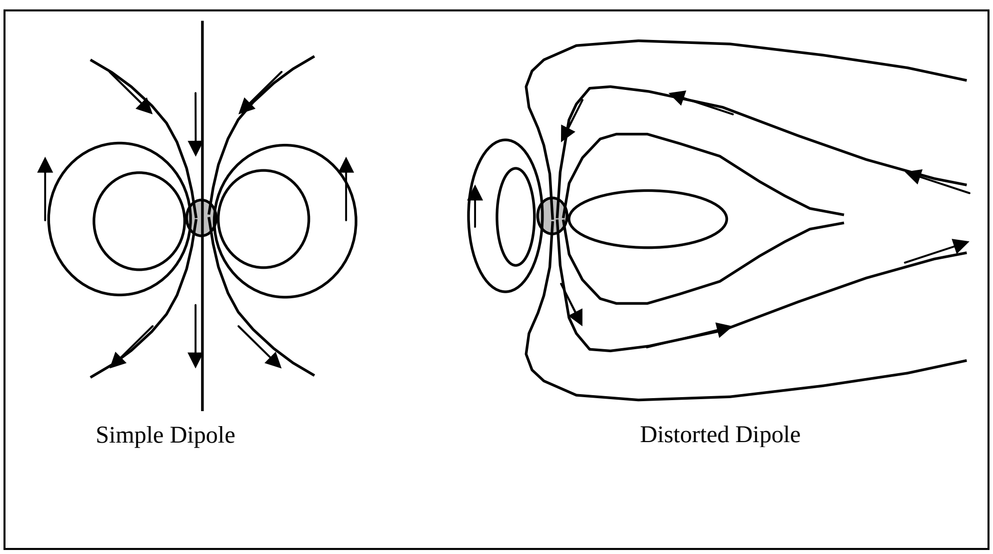


Figure 3.4. The Distortion of Earth's Magnetic Field by the Solar Wind. On the left is a simple dipole magnetic field configuration**.** On the right is Earth's magnetic field as distorted by an

external flow. The Earth's north magnetic pole is currently at the south geographic pole and vice versa.

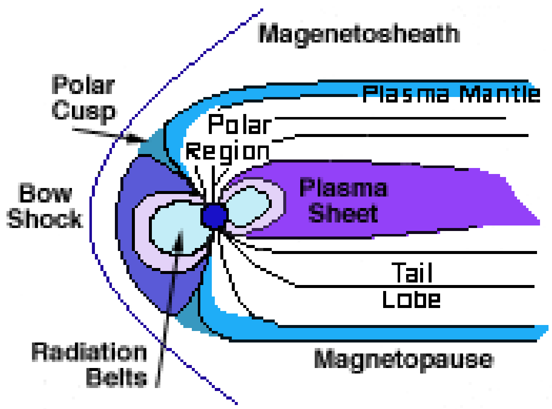


Figure 3.5. A Depiction of Earth's Bow-shock, Magnetosphere, and Radiation Belts. The bowshock, indicated in dark blue, typically forms about 15 R_E upstream of Earth and has a curved shape. This shock extends about 10 R_E either side of Earth. Solar wind flow is depicted in yellow. Magnetospheric field lines are shown in red. As we show, the magnetosphere is not really a sphere. It is more like a hemisphere with an attached cylinder that ultimately takes on a bullet or tear-drop shape. (Courtesy of NASA)

Magnetospheric plasma originates in Earth's upper atmosphere and in the solar wind. Although much of the magnetosphere is a near-vacuum by Earth standards, its high plasma density, compared to interplanetary space, allows energy in the solar wind to drive electric currents and set plasma in motion within the magnetosphere and Earth's upper atmosphere. We know two important effects of this behavior: 1) solar wind disturbances energize plasma even within Earth's protective magnetic shield, and 2) the solar wind induces magnetospheric flows that are disconnected from Earth's rotation.

Magnetotail Contained within the volume of the magnetotail are regions of relatively low and high densities of plasma. The ***magnetotail lobes***, one in each hemisphere, have relatively low-density, cool plasma. The ***plasma sheet*** within the central magnetosphere has a denser and more energetic plasma population. During periods of geomagnetic storms, this plasma invades the orbit of geosynchronous satellites (6.6 R_E) and bathes the satellites in a soup of energetic ions and electrons. This plasma bath leads to potentially lethal space weather impacts for instruments on geosynchronous satellites.

Inner Magnetosphere Close to Earth (within 5 R_E), Earth's magnetic field resembles a dipole associated with a giant bar magnet. The relatively strong dipole field lines near Earth act as a trap for energetic plasma. In 1958 an instrument onboard *Explorer 1,* built by James Van Allen, measured unexpectedly high values of ionizing radiation coming from a region within the dipolar magnetic field lines. Today we call this region of near-space the ***radiation belts*** or sometimes the ***Van Allen belts*** , (see Figure 3.5). The belts are doughnut-shaped and centered on Earth's magnetic equator. Spacecraft that operate in or near the radiation belts must carry extra shielding to prevent damage to instruments and components from energetic particles trapped in the belts.

Occupying much of the same region of space as the radiation belts is a torus (doughnut-shaped) region of higher density but significantly lower temperature plasma with the hole aligned with Earth's magnetic axis called the ***plasmasphere***. This plasma consists of hydrogen ions (protons) and electrons from Earth's upper atmosphere. The ***plasmapause*** (sharp outer edge of the plasmasphere) is usually 4-6 Earth radii from Earth's center (19,000-32,000 km above the surface). Inside the plasmapause, the plasma rotates with Earth. The inner edge of the plasmasphere, which intermixes with Earth's upper atmosphere, is the altitude at which protons replace oxygen as the dominant species in the atmospheric plasma. This edge usually occurs at about 1000 km (600 mi) altitude. The plasmasphere serves as a vital link between Earth's magnetic domain and Earth's atmosphere.

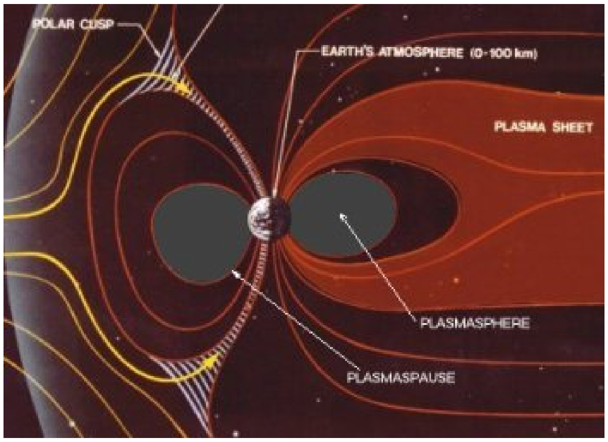


Figure 3.6. A Depiction of Earth's Plasmasheet, Plasmapause and Plasmasphere. Here we show a cross-section from noon to midnight of the inner magnetosphere. The plasmasheet bridges the outer and inner magnetosphere. It is an inner magnetosphere feature at high latitudes. The lower-latitude and lower - energy region that bridges between the inner magnetosphere and upper atmosphere is the plasmasphere. The plasmapause is a variable boundary separating particles that are primarily from the Earth's atmosphere from those primarily from the Earth's magnetosphere. (Courtesy of NASA)

3.4 Earth's Upper Atmosphere is Dominated by Space Weather

The Edge of Space

Earth's upper atmosphere occupies a strategic position—the edge of space. For our purposes, it is a portion of the satellite (and rocket) operational arena, a source of matter for the regions of space outside the sensible atmosphere, and a protective blanket shielding the regions below from many energetic particles and photons. Many astronautical engineers designate the edge of space at about 130 km; because that is the lowest altitude at which a spacecraft can successfully make one full orbit. Nonetheless, we stick with our claim of the region at or above 50 km as near-space, because interesting space physics-related effects occur at this level and above. This shell of molecules, atoms, and ions, extending down to 50 km, interacts with (1) the Sun by photons, (2) the magnetosphere through plasma and electromagnetic interactions, and (3) the atmosphere below using waves and gravity.

Driven by energy and momentum from above and below, the upper atmosphere's behavior is quite complex and quite hot. To organize this complexity (and perhaps reduce it), we discuss four means by which scientists typically categorize upper atmospheric behavior: mixing, temperature, retention, and degree of ionization. Each category in Figure 3.7 contains the word "sphere." In this instance, the term is at least geometrically appropriate. Close to Earth, gravity becomes a dominating force, and much of the material in the upper atmosphere is stratified and constrained to a spherical volume about Earth.

Atmospheric Classification

Mixing. The frequency of particle collisions is the key to the mixing state of the atmosphere. When collisions are numerous, the atmosphere is well mixed. Strong mixing leads to a homogenous ratio of atmospheric constituents. Between Earth's surface and 100 km, the chemical mix of atmospheric constituents is roughly 78% N_2, 21% O_2 and 1% other. The region below 100 km is the ***homosphere.*** Above 100 km however, the lower density of particles leads to fewer collisions. Therefore, atoms and molecules tend to stratify with more massive particles remaining at relatively low altitudes, and the less massive ones diffusing to higher levels. The stratified region is the ***heterosphere*** (as in heterogeneous). A significant consequence of this stratification is the relative abundance of atomic oxygen above 300 km where many LEO satellites orbit. Atomic oxygen is exceedingly reactive. It attacks spacecraft components and reduces mission lifetime.

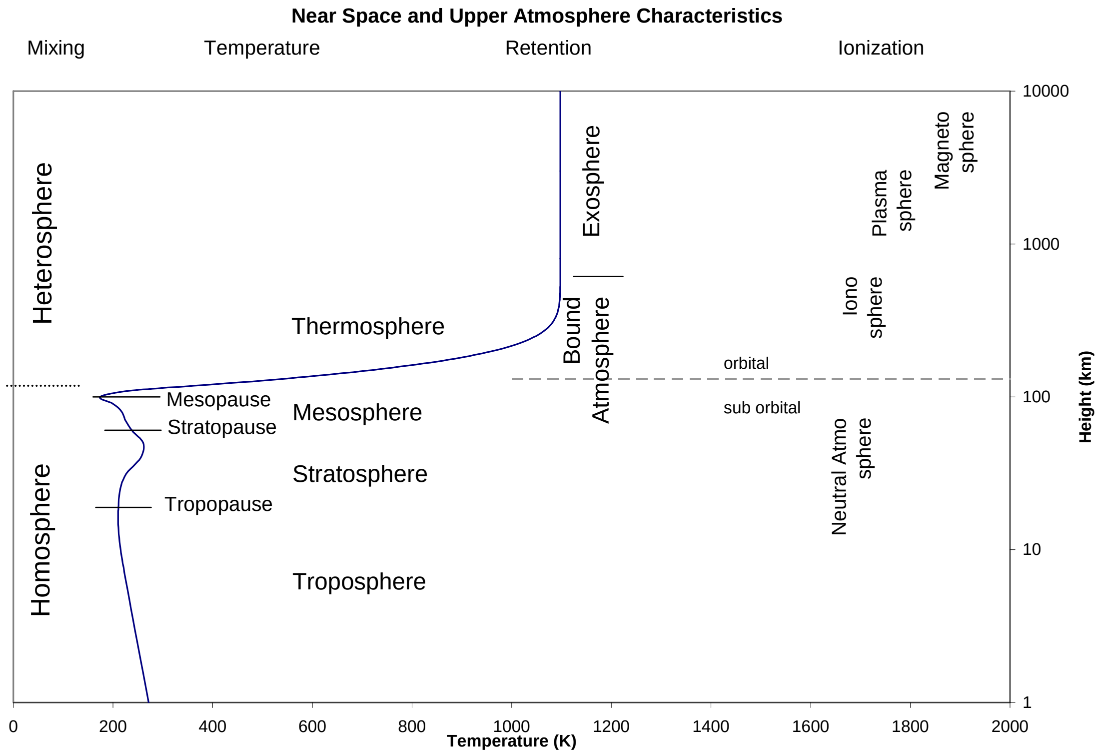


Figure 3.7. Classifications for the Upper Atmosphere. The central curve shows temperature variation with height. We note that the vertical scale is logarithmic.

Temperature. Figure 3.7 shows the full temperature range of Earth's thermal envelope. Temperatures near Earth's surface are rather cool. Stratospheric temperatures show the influence of ozone absorption of solar ultraviolet (UV) radiation. Higher in the ***mesosphere****,* efficient absorbers are largely absent, so radiative cooling creates low temperatures relative to the surrounding regions. Above 100 km, chemical species with an affinity for absorbing solar radiation again abound. Though the density of these species is low, solar photons are abundant, meaning individual particles in this region, called the ***thermosphere****,* share in a wealth of solar energy. With high available energy per particle, temperatures rise rapidly. Exospheric temperatures exceed 1000 K, on average, over the solar cycle. As solar emissions vary with the solar cycle, so do thermospheric temperatures and densities. When thermospheric densities vary, low-Earth orbits are perturbed by variations in atmospheric drag.

Retention. Earth's gravitational force is greatly reduced in the most-distant atmospheric region, the ***exosphere***. Plasma particles heated by various solar and magnetospheric processes fight against gravity. Typically only the lighter atmospheric elements occupy this upper domain. Some of these particles may gain sufficient energy to achieve escape velocity from the atmosphere. Their ballistic trajectories allow them to exit to the plasmasphere and magnetosphere. Below about 500 km, frequent collisions and gravity thwart attempts at escape, and particles are retained unless energized by extreme space weather storm effects. The lower boundary of this region, known as the ***exobase***, is typically near 500 km (300 mi) but may be lower during higher solar activity. The upper reaches of the exosphere blend into the plasmasphere at 10,000 km. Most low Earth-orbiting (***LEO***) satellites operate in the exosphere.

Ionization. Existing within the thermosphere is perhaps the most dynamic of the upper atmosphere spheres: the ionosphere. Searing solar electromagnetic radiation heats and excites atoms and molecules in Earth's upper atmosphere. It also rips

FOCUS ON: The Ionosphere

The ionosphere serves as a high altitude reflector for short-wave broadcasting and long-range communication. During the occurrence of a solar flare, the enhanced X-ray radiation from the Sun causes the electron density in the lowest layer of the ionosphere to increase by a large factor. This increase results in a ***radio blackout*****–**the immediate and large-scale absorption (rather than reflection) of high-frequency radio waves and subsequent disruption of short-wave communication over Earth's sunlit hemisphere. In addition, beginning tens of hours after a solar flare, the global electron density in the upper levels of the ionosphere may undergo substantial variations because of the interaction of the disturbed solar wind with the near space environment. These variations can last for several days after disturbance onset. At high latitudes, a significant fraction of the ionization is produced by charged particles that have been dumped from the magnetosphere during times of magnetic storms and also by charged particles from the Sun that have been diverted to these latitudes by the geomagnetic field.

During disturbed times, instabilities arise in the ionospheric plasma. These instabilities cause the initially (relatively) homogeneous plasma to develop density turbulence, typically magnetic field-aligned, with scale sizes on the order of centimeters to hundreds of kilometers. Electromagnetic waves propagating through this turbulence are scattered, resulting in ***scintillation*** or twinkling of signal sources, analogous to the twinkling of starlight by density turbulence in the atmosphere. These scintillations lead to strong disturbances in the radio band up to GHz frequencies, thereby disrupting communications and some navigation systems, such as the Global Positioning Satellite (GPS) system signals. In addition, the scattering can blind radar tracking (e.g., over-the-horizon radars) and disrupt (or sometimes improve) communications. Currently scientists are trying to find ways to use these scintillation and scattering effects as a diagnostic tool for space weather.

molecules apart and tears electrons from some fraction of their parent particles. The free electrons and positive ions then form several weakly ionized layers of plasma. These ionized layers constitute the ***ionosphere***. Because of the ***diurnal***, (day-night) nature of incident solar radiation, the ionization is more extensive during the day than during the night. Solar photons are not the only culprit in ionization. Energetic particles flowing from the nightside magnetosphere also have a role in creating the high-latitude ionosphere.

3.4 Meteors and Space Dust Affect the Space Environment

As Earth orbits the Sun, it constantly intercepts the remains of old cometary tails and space dust. This material ablates as it falls into the atmosphere and creates small ionization trails in its wake. We call these ***meteor trails*** or meteor echos. The elongated paraboloid of ionized air can be many kilometers long. Occurring at an atmospheric height of about 85-105 km (50-65 mi), this ionized trail of meteor debris is capable of reflecting radio waves from transmitters on Earth. Meteor trail reflections are brief, however. As the trail rapidly diffuses into the surrounding air, it quickly loses its ability to reflect radio waves causing most reflections to last less than 1 second. Occasionally, a large meteor may create a trail capable of reflecting radio waves for several minutes. During times of enhanced meteor activity, some forms of communication may be improved. On the other hand, radar beams may experience anomalous reflection known as radar clutter. In the worst cases, some radar systems are rendered ineffective. Meteoroids and meteors also represent a collisional hazard to spacecraft. Even tiny fragments endanger spacecraft components because they strike at such high speeds.

3.6 Space Weather Effects in Earth's Lower Atmosphere and at Earth's Surface

Galactic cosmic rays and their Sun-generated cousins, ***solar energetic particles (SEPs)***, penetrate Earth's atmosphere. In the stratosphere and upper troposphere, these particles create radiation exposure to avionics, flight crews, and passengers on high-latitude flights. The European Council has recommended that aircrews be treated as personnel receiving occupational radiation exposure. As such, crew annual radiation dose must be monitored (Jansen, et al., 2000).

Penetrating cosmic rays and their by-products may influence cloud formation by changing the ionization state of cloud condensation nuclei. Solar cycle variations of cloud cover are an active area of research (Tinsley, 2000). Energetic particles have been identified as a source of soft errors in stored data on computer systems. Computer systems that operate in high, mountainous regions or where the magnetic field is slightly weak are more susceptible to cosmic ray damage.

Extreme SEP events, associated with very energetic solar flares are sensed in the troposphere and at the ground. The most energetic of these particles create chemical compounds in the atmosphere that subsequently drift to the ground. Snow in the polar cap ice sheets becomes a recording device for the great solar energetic particle events associated with the largest solar flares. Approximately 125 impulsive events have been identified in the polar ice cores for the interval 1561-1950 (McCracken et al., 2001).

Electrons energized in Earth's magnetosphere also penetrate into the stratosphere. In the upper regions of the stratosphere, energetic electrons alter ozone behavior and create short-term reductions in ozone density. Scientists are attempting to determine if a solar cycle variation of upper level ozone exists. Researchers are quite certain a link exists between stratospheric winds and the solar cycle (Labitske and van Loon, 1987). Solar cycle variations in ultraviolet wavelength radiation from the Sun appear to alter the amount of ozone and the distribution of ozone heating between 30 and 50 km in Earth's atmosphere. In turn, this heating affects the stratospheric circulation. Scientists are actively investigating the link between altered stratospheric circulation and the location of the northern hemisphere winter storm tracks.

Earth's inhabitants are rather comfortably shielded from almost all direct solar and solar wind effects. However, space weather disturbances of the magnetic field and plasma in the magnetosphere and upper atmosphere propagate to the surface and even to the ocean floor. As we discuss shortly, surface magnetic field disturbances provided one of the first historical clues about what we now call space weather. Space weather effects at the ground include magnetically induced electrical surges in power lines that disrupt power grids and similar effects in unprotected long distance communication lines on land or under the sea. An extreme example of this resulted in the 1989 Hydro-Quebec power outage. Even fiber optic systems can be compromised if their signal-amplifying equipment is powered by long metallic wires.

Now that we have completed a broad description of the space environment, we realize that particles, fields, and photons figure predominantly in space weather.

4. SUMMARY

Space is not empty, rather it contains a tenuous gas of charged particles called plasma. Much of this plasma comes from out-gassing of our local star, the Sun. While the Sun yields a continuous flow of the solar material into the interplanetary environment, it also has episodic events that flood the space environment with energetic particles and magnetic fields. The episodic events, called space weather, are known to interfere with modern technology systems on orbit and sometimes on the ground. The continuous background emissions give rise to the space environment.

The Sun's influence extends to nearly 100 times the Sun-Earth distance. Within this volume of space the Sun's radiation and outer atmosphere influence all planets, forming magnetospheres around many and ionospheres around all. Our local ionosphere and magnetosphere are the sites of considerable energy exchange with the solar emissions. To date most space weather has been identified with these spheres of influence. We are currently learning that the energy does not stop at the ionosphere, but rather extends into the atmosphere and all the way to the ground.

As space becomes ever more important to the conduct of daily life, space professionals need to be aware of the many possible impacts of space weather and space environment interactions.

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