# Chapter 4

# Solar-Terrestrial Interactions

## Section 1.—The Terrestrial Space Environment

The effects of the radiation and particles that stream out from the Sun would be quite deadly for the inhabitants of Earth if not for two protective features. The first one is Earth's atmosphere, which blocks out the x-rays and most of the ultraviolet radiation. When x-ray or ultraviolet photons encounter the atmosphere they hit molecules and are absorbed, causing the molecules to become ***ionized***; photons are re-emitted but at much longer (and less biologically destructive) wavelengths. The second protective mechanism is the Earth's magnetic field. This protects living organisms from the charged particles that reach the planet steadily as part of the solar wind and the much greater bursts that arrive following mass ejections from the Sun. When charged particles encounter a magnetic field, they generally wrap around the field lines. Only when the path of the particle is parallel to the field can it travel without deflection. If the particle has any motion across the field lines it will be deflected into a circular or spiral path by the Lorentz Force. Most charged particles in the solar wind are deflected by the Earth's magnetic field at a location called the ***magnetopause***, about 10 Earth radii above the Earth on the day side. Inside the magnetopause, the Earth's magnetic field has the dominant effect on particle motion, and outside, the solar wind's magnetic field has control.

Until 1960, Earth's magnetic field, called the geomagnetic field, was thought to be a simple ***dipole field*** like that of a bar magnet. We do not yet know the details of what produces the geomagnetic field, except that there must be currents circulating inside Earth, probably associated with the molten core. With the discovery of the ***solar wind***, physicists realized that the magnetic field of Earth is pushed away from the Sun. The solar wind exerts a pressure on Earth's magnetic field which compresses it on the Sun-facing side and stretches it into a very long tail on the side away from the Sun. This complex magnetic envelope is called the magnetosphere (Figure 4–1). On the Sun-facing side, the solar wind compresses the magnetosphere to a distance of about 10 Earth radii; on the downwind side, the ***magnetotail*** stretches for more than 1000 Earth radii. The magnetosphere is filled with tenuous plasmas of different densities and temperatures, which originate from the solar wind and the ***ionosphere***. The ionosphere is the highly charged layer of Earth's atmosphere which is formed by the ionizing effect of solar radiation on atmospheric molecules. In the early 1960s, solar physicists began to realize that the solar wind carries the Sun's magnetic field out to the far reaches of the solar system. This extension of the Sun's magnetic field is called the ***interplanetary magnetic field*** and it can join with geomagnetic field lines originating in the polar regions of Earth. This joining of the Sun's and Earth's magnetic fields is called ***magnetic reconnection***, and happens most efficiently when the two fields are anti-parallel. Through reconnection the magnetic fields of Sun and Earth become coupled together.

Solar wind particles approaching Earth can enter the magnetosphere because of reconnection and then travel along the geomagnetic field lines in a corkscrew path (Figure 4–2). Positive ions and electrons follow magnetic field lines (in opposite directions) to produce what are called field-aligned currents. The solar wind and the magnetosphere form a vast electrical generator which converts the kinetic energy of solar wind particles into electrical energy. The power produced by this magnetohydrodynamic generator can exceed $10^{12}$ watts, roughly equal to the average rate of consumption of energy in the United States today! The very complex plasmas and currents in the magnetosphere are not fully understood. Some of the solar wind particles travel back along the magnetotail in currents which make the tail

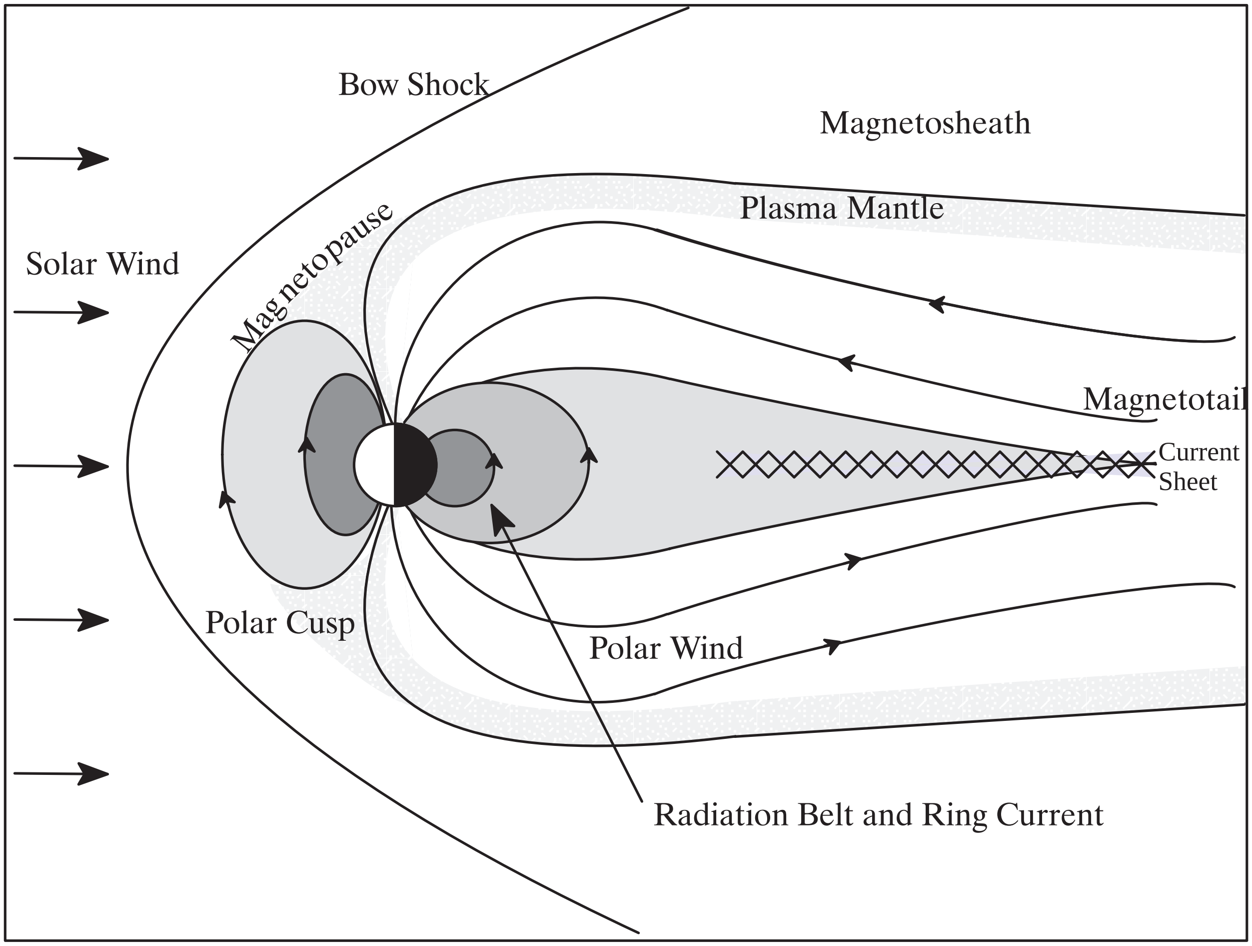


***Figure 4–12.****—A "side view" of the Earth and magnetosphere showing some of the important regions.*

look like it has a giant battery in it. Some particles follow the field lines that converge near the polar regions of the earth and bounce back and forth, trapped in a magnetic mirror. Other particles are injected into the ionosphere and form an oval of light around the polar regions of Earth, called the ***auroral ovals***.

The auroras are caused by electrons colliding with molecules in the ionosphere (Figure 4–13). These collisions both ionize the molecules and excite them into emitting a wide spectrum of light from infrared to ultraviolet. The most common auroral emission is a whitish-green light with a wavelength of 558 nm, which is produced by atomic oxygen. A beautiful pink emission comes from excited molecules of nitrogen. The large, moving curtains of color that result from molecular excitation are familiar to people of the far northern and southern latitudes, although they can be seen from anywhere on Earth if the conditions are right. Auroras occur near both the north and south polar regions of Earth, and the two displays are nearly mirror images of each other. The northern lights are called the ***aurora borealis***, while the southern lights are called the ***aurora australis***.

Since the early 1900's scientists have suspected that both the auroras and the variations in the Earth's magnetic field must be caused by some kind of currents which flow in the upper atmosphere. Today we know that there are many currents which flow in the magnetosphere caused by the very complicated interplay between the solar wind and Earth's magnetic field. Although these currents are only partially understood at present, the one that has been studied most extensively is the ***Birkeland current***, which is associated with the auroras. When the solar wind encounters the Earth's magnetic field about 50,000 km above Earth, an ***electromotive force*** (EMF) of about 100,000 volts is generated. This

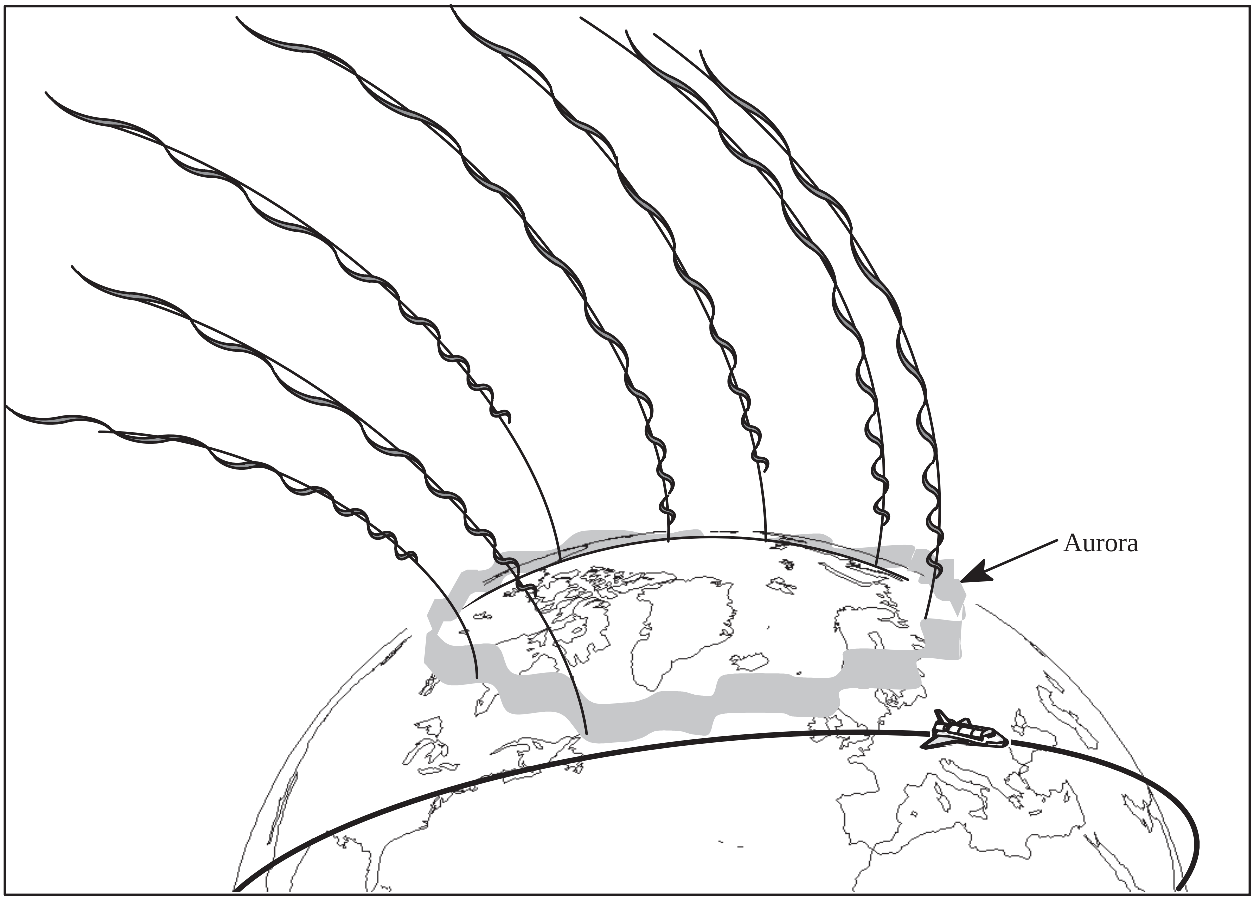


*Figure 4–13.—Energetic electrons travel along the geomagnetic field lines towards the polar regions, striking the upper atmosphere and resulting in the display of lights called aurora.*

applied EMF is distributed throughout the magnetosphere and Earth's upper atmosphere, much as the voltage from a electric utility generator is distributed around a power grid. A portion of the solar-wind-generated EMF, perhaps 10,000 volts, accelerates electrons down magnetic field lines into the ionosphere at altitudes of about 100 km. These electrons first travel horizontally and then back up to the upper atmosphere to form a closed circuit. Although this circuit has many similarities to a simple circuit with wires and a battery, it is also very complex since it occurs in three-dimensional space and varies wildly in time as the solar-wind intensity changes. Currents as high as one million amperes are common, and the total power produced in this giant generator can be as much as $3 \times 10^{12}$ watts! It is the high-speed electrons near the bottom of this current loop which collide with molecules and atoms of the atmosphere that produce the auroras. The strongest auroral emission comes from altitudes of about 100 km. As with any simple circuit, energy is dissipated as the electrons flow around the loop. Some of this energy shows up as the light of the auroras, but most of it becomes thermal energy—heating the atmosphere. Another important result of the Birkeland current is that, like any current loop, it produces a magnetic field. This field extends down to the Earth's surface where it adds to the geomagnetic field, causing it to fluctuate (see Activity 7). These fluctuations in magnetic field can then induce currents in the Earth's surface, or in conductors like power lines or pipelines. All of this is determined by the behavior of the solar wind reaching Earth, which in turn is determined by the events taking place on the Sun. When the auroras are highly visible, often it is a sign that there is a higher flux of particles from the solar wind. It also means that many of our electronic systems on Earth may become disrupted or even damaged.

## The Cause of the Aurora

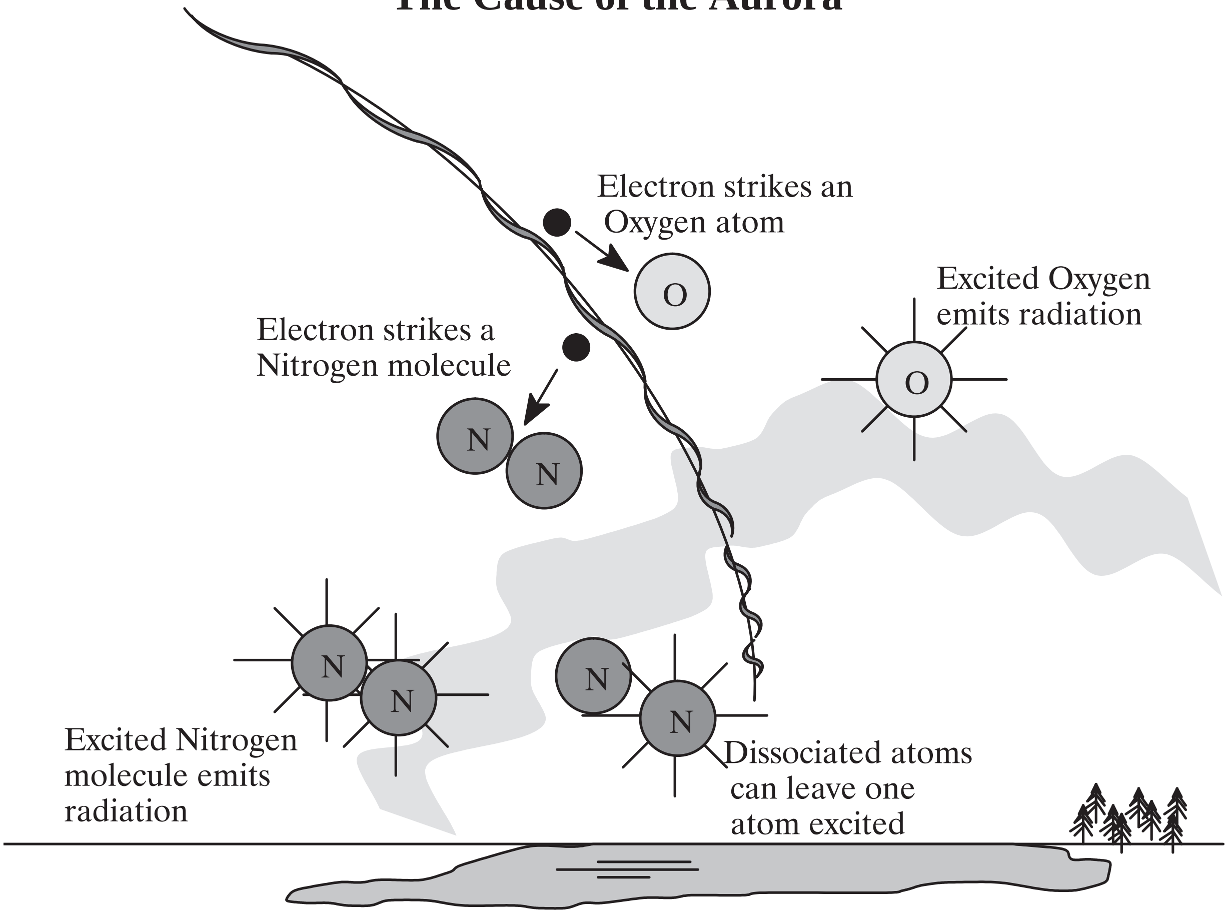


***Figure 4–14.****—High-speed electrons strike atoms and molecules in the lower ionosphere, causing them to emit visible light seen as the aurora.*

### Section 2.—Terrestrial Effects

The complex coupling of the solar wind and the geomagnetic field produces many effects near Earth. Earth is embedded in the outer atmosphere of the Sun and therefore is affected by events which occur in the surface layers and coronal regions of the Sun. Terrestrial effects are the result of three general types of conditions on the Sun: eruptive flares, disappearing filaments and coronal holes facing Earth.

***Flares*** are short term brightenings that last for minutes or hours. They usually occur near active regions on the Sun where abrupt changes in magnetic field are taking place. A complete understanding of the conditions and sequence of events associated with flares is still lacking, but generally when a flare begins, plasma is accelerated out from the Sun. This plasma usually returns in an arching fashion and, upon colliding with the denser material of the chromosphere, emits ***Bremsstrahlung x-rays***. In more eruptive flares, plasma is thrown completely away from the Sun, and this radiation can have a significant effect if it reaches the Earth environment.

Long-term eruptive activity is usually associated with the disappearance of ***filaments***. Filaments are the long, string-like features which appear prominently in Hα photos of the Sun (Figure 3–6). They hang like clouds in the low chromosphere for days or weeks then disappear, in most cases by dissipating, much like Earth clouds “burn off.” In other cases, though, filaments disappear by rising up, away from the chromosphere to form giant arching prominences.

When prominences appear at the limb of the Sun, where we can see them from the side, spectacular photos can be taken. In some cases prominences break away from the Sun and large bursts of plasma are hurled outward into space.

The third source of mass traveling out from the Sun is the ***coronal hole***, easily seen as a dark region in an x-ray photo of the Sun (Figure 3–10). Magnetic field lines extend outward from coronal holes, in contrast to other regions of the Sun where field lines arch back to connect (Figure 3–3). The open field structure of coronal holes acts like a conduit for low density plasma which streams out steadily. Coronal holes reside permanently near the poles of the Sun, and the solar wind streaming out from these generally does not reach the Earth. But during some rotations of the Sun, coronal holes form at lower latitudes, facing the Earth (Figure 3–8), and these act like a broadly focused fire hose spraying the Earth with a high intensity of charged particles.

We now know that mid-latitude coronal holes (usually occurring during the phase of solar activity following solar maximum) are sources of high-speed solar wind streams, which buffet Earth in synchronism with the 27-day solar rotation. Previously the cause of these recurring geomagnetic storms was unknown, so the regions were called M-regions, M for mysterious. Non-recurrent major storms and large geomagnetic storms are almost always associated with coronal mass ejections (CMEs) and with the shock waves associated with CMEs.

Several centuries ago, the disruptive effects of the Sun were totally unnoticed by humans. But as technology developed that utilized currents, conductors, and eventually electromagnetic waves, the disruptive effects of the Sun became evident. Early telegraph systems in the 1800s were subject to mysterious currents that seemed to be generated spontaneously. It was not until World War II, when radio communications were heavily relied upon, that solar disturbances were recognized as a serious problem. From that time on, our reliance on electronic technology has grown exponentially and so has the disruptive potential of the Sun. The massive collapse of the Hydro-Quebec power system in 1989, which resulted in the temporary loss of 9450 megawatts of electrical power, probably marked the moment when more than just the scientific community took solar disturbances seriously. A few of the major effects that are a problem today are described below.

## Geomagnetically Induced Currents

When an intense surge of solar wind reaches Earth, there are many changes which occur in the magnetosphere. The day side of the magnetosphere is compressed closer to the surface of Earth and the geomagnetic field fluctuates wildly. This type of event is generally called a ***geomagnetic storm***. During a geomagnetic storm the high-latitude currents which occur in the ionosphere change rapidly, in response to changes in the solar wind. These currents produce their own magnetic fields which combine with Earth's magnetic field. At ground level, the result is a changing magnetic field which induces currents in any conductors that are present. These are called geomagnetically induced currents, which often flow through the ground unnoticed by humans. But when good conductors are present, like pipelines and electrical power transmission lines, the currents travel through these as well. These currents are the result of voltages that are induced during geomagnetic storms. Voltages as high as 10 volts per mile have been measured. Although this may seem small, it leads to a potential difference of 10,000 volts in a 1000 mile long pipeline or power line. In 1957, voltage differences of 3,000 V were recorded along a trans-Atlantic cable between Newfoundland and Ireland.

Induced currents are much more serious at higher latitudes, near the auroral oval, and in areas which lie above large deposits of igneous rock. Because igneous rock has a low conductivity, the induced currents tend to take a path through man-made conductors. In pipelines, these currents cause increased corrosion and the malfunction of flow meters. The Alaska pipeline has carried as much as 1000 A during geomagnetic storms. In large power systems, like Hydro-Quebec, surges of induced current overload transformers and capacitor banks, causing damage and shutdown. The problem is worsened by the fact that geomagnetically induced currents are largely direct current, while all of our power systems are alternating current. Hydro-Quebec was especially vulnerable because it is located fairly far north and it sits above huge igneous rock formations. Since 1989 power companies have become very concerned about geomagnetic storms. With better warning, power plants can protect themselves to some extent, but there is still a high degree of vulnerability. Electrical engineers are attempting to design protective mechanisms, but as we build bigger power systems, with more miles of transmission lines, our vulnerability increases.

## Communications

Many of our communication systems utilize the ionosphere to reflect radio signals over long distance. Because the ionosphere is altered during geomagnetic storms, these reflected communications are often distorted or completely fade out. Although TV and commercial radio broadcasts are rarely affected, longer distance communication, like ground-to-air, ship-to-shore, Voice of America, and amateur radio, are frequently disrupted. A number of military systems, like early warning, over-the-horizon radar, and submarine detection, are greatly hampered during times of high solar activity. Some types of radio communication can be “jammed” by increased levels of radio output from the Sun. The jamming of air traffic control frequencies can create dangerous situations for air travelers. There are also many navigation systems that are in widespread use today that are vulnerable to solar disturbances. Airplanes and ships use signals from transmitters located around the world to triangulate their positions. Solar activity can cause these systems to give location information that is inaccurate by several kilometers. If navigators are alerted that a proton event or geomagnetic storm is in progress, they can switch to a backup system.

## Satellites

Satellites are placed in orbits that are above most of Earth’s atmosphere so that there is little frictional drag affecting them. Communications satellites, in geosynchronous orbits, are about 6 Earth radii up. Low-orbiting satellites, which speed around the earth every 2 hours or so, are barely above the Earth’s atmosphere. During times of high solar activity there is an increase in ultraviolet radiation and auroral energy input, and this heats up Earth’s atmosphere, causing it to expand. The low-orbiting satellites then encounter increased drag which causes them to drop in their orbits. Satellites with propulsion systems, and the fuel to run them, can be raised back to their correct orbits, but some of the satellite orbits will decay causing them to fall to Earth; this was the fate of Skylab. The high satellites, in geosynchronous orbits, are not subject to drag from atmospheric heating, but they are subjected to the solar wind. These satellites are usually well protected from solar wind particles by the magnetosphere which normally has a minimum thickness of about 10 Earth radii. But when a surge in the solar wind reaches Earth, the front side of the magnetosphere can be compressed or eroded away to a thickness of about 4 Earth radii. This places the high satellites outside the protective shield of the magnetosphere. The impact of high speed particles has a corrosive effect on satellites, and charge buildup can result from these particles. Electrical discharges can arc across spacecraft components causing damage.

## Biological Effects

For much of the world’s population, living in the mid-latitudes, there is probably very little direct effect when solar activity occurs. Protons and electrons do not reach Earth’s surface because of the shielding of the magnetosphere. However, aircraft flying high altitude polar routes are subject to a greater flux of protons because the magnetic shielding is weak near the poles. It is not yet known how serious this is for passengers, but some experts advise pregnant women not to fly on polar routes during times of high solar activity. There is also great concern for the safety of astronauts during solar proton events. Astronauts during the Space Shuttle program were fairly safe because the Shuttle stayed in a relatively low orbit, well protected by the magnetosphere. The spacecraft itself provided good shielding from particles, but when astronauts were outside the spacecraft, they were in much greater danger. Energetic protons can penetrate deep into the magnetosphere and potentially expose astronauts to a dangerous dose of radiation during the very rare, intense radiation storms. Space missions which go outside the magnetosphere, like Moon or Mars missions, will have to deal with the problems of solar disturbances. A trip to Mars will take 2 to 3 years, and the problems of exposure to solar effects will be significant. The International Space Station (ISS) has been in low Earth orbit since 1998 and continuously occupied since late 2000. Astronauts occasionally must work outside for long periods of time, and can become vulnerable to solar radiation. The ability to predict dangerous energetic proton (radiation storm) events, and give advanced warning is one of our most powerful protections.

There are a number of other biological effects, some substantiated and some not. It is well known that many animals use Earth's magnetic field to navigate. This explains how migratory birds can fly thousands of kilometers across oceans and not get lost. It is not known exactly how these animals can detect Earth's field, but studies on homing pigeons have shown that there are certain tissues in the head and neck regions that contain iron-rich molecules with magnetic properties. What is known with certainty is that animals with magnetic navigational abilities tend to become disoriented during geomagnetic storms when the geomagnetic field fluctuates. Some researchers are beginning to suspect that humans are susceptible to magnetic effects. A correlation has been made in Israel between solar activity and a higher death rate for heart disease patients who are near death. Studies in Hungary claim a correlation between high solar activity and increased industrial and traffic accidents. There are even people today who are looking for correlations between solar activity and the stock market. Apparently no one has yet gotten rich from this tenuous connection!

## Section 3.—Forecasting and the Future of Solar Physics

Serious interest in being able to predict solar activity, and its effects on Earth, began during World War II. Electronic technologies, such as radio communication, radar, and magnetic submarine detection, were heavily relied upon for the first time and it became clear that these technologies could be seriously disrupted by the Sun. After the war, more uses were developed for electronic technologies, especially with the birth of the space program. During the 1950s, there were attempts to pool resources world-wide to improve forecasting, but this was to end in the late 50s with the launch of the Soviet Sputnik and the beginning of the cold war. Anticipating the Moon mission of 1969, NASA became heavily involved because of the danger to astronauts. This reached a peak in 1973 with the Skylab missions. Since that time, financial support for solar research has decreased, yet our need to be able to forecast solar activity continues to increase as vulnerable technologies become more widespread. Undoubtedly, the power outage at Hydro-Quebec in 1989 underscored the importance of solar forecasting.

In the early days of solar forecasting, it was assumed that when a CME occurred from the Sun there would be a very predictable geomagnetic disturbance on Earth within a few hours or days. It was therefore believed that improved forecasting was just a matter of making better observations of the Sun so that flares and other mass ejections could be detected immediately after they occurred. But experience soon showed that the effects on Earth did not correlate so simply with events on the Sun; not all mass ejections had a noticeable effect on Earth, and sometimes there were geomagnetic storms when there was no apparent eruptive activity on the Sun.

We now know that how the Sun's magnetic field connects with the geomagnetic field makes a big difference in how solar activity affects Earth. When a mass of plasma is ejected from the Sun, the plasma travels outward in the solar wind. These plasma bursts have their own magnetic fields which are carried along with the plasma. How these fields are oriented when they arrive at Earth determines whether magnetic reconnection will occur. When the direction of the solar wind field is opposite the direction of Earth's field, magnetic reconnection occurs, and the ***geomagnetosphere*** essentially becomes a part of the solar magnetic field. In this condition, Earth is much more prone to the effects of the solar wind. Solar wind particles can enter the magnetosphere more easily, and those already within the magnetosphere are energized. Changes in solar wind magnetic fields cause wild fluctuations in the magnetospheric fields. In response to these fluctuations, in accordance with Lenz's Law, massive currents flow throughout the magnetosphere. It is these high altitude currents that induce voltages at ground level. If the magnetic field of the solar wind is in the same direction as the Earth's field, then magnetic reconnection does not occur and the magnetosphere is much more separated and protected from the solar wind. Under these conditions, the effects of solar mass ejections are much less significant. In order to know what is going to happen on Earth we must know not only what happened on the Sun but also the nature of the magnetic fields that are carried along with the solar wind. This is one reason why the DSCOVR satellite is so essential to space weather forecasters; to determine the nature of the solar wind before it arrives. While space weather forecasting remains a very difficult endeavour, satellites such as DSCOVR, SOHO, and GOES have made collection of data more accurate and timely; thereby increasing forecasting accuracy of major space weather events.

The NOAA Space Wether Prediction Center (SWPC) in Boulder is nation's official source for space weather alerts and warnings; and is one of the world centers that makes forecasts of solar and geomagnetic activity. Each day forecasts out at least three days are issued for the likelihood of solar flares and intensity, proton events, x-ray flux, and geomagnetic storms. These forecasts are used by a multitude of customers across the nation and around the world whom are concerned with a variety of space weather vulnerable systems, communications, navigation, or health. SWPC is a worldwide nerve center for thousands of data streams, including x-ray and particle flux data from the GOES satellites, H$\alpha$ images and magnetograms from observatories around the world, measurements of the geomagnetic field at many locations, and 10.7-cm radio levels from several radio telescopes. Each day the features of the solar disk are analyzed and mapped so that the evolution of active regions, coronal holes, filaments, and neutral lines may be carefully studied. Forecasters consider all of this information when making their forecasts, even so, the science of solar physics, the magnetosphere, and the interplanetary medium are still not well understood. Many partial mathematical models have been developed, but there is no total comprehensive model of the Solar-Terrestrial environment; although a few advancements in heliophysics have resulted in some new forecast models of prediction.

In most cases, the ability to predict the behavior of nature comes from a mathematical model. For example, the motion of an object falling in a gravitational field can be modelled using the mathematical expression $v = g \times t$ . Earth weather forecasters have been trying for the last 30 years to construct a mathematical model of the global weather using the very complex equations of fluid dynamics to describe the circulation of the oceans and atmosphere. Even with the best supercomputers to run these models, it has proven impossible to precisely model Earth weather. Modelling the solar-terrestrial environment is vastly more complex. The physics necessary to do this includes not only fluid dynamics but also Maxwell’s equations. This combination is known as ***magnetohydrodynamics*** (MHD), and at the present time the equations of MHD cannot be completely solved analytically. Numerical solutions exist which involve the use of a computer in a “trial and error” fashion. Numerical solutions, however, can give incorrect results and at best are an approximation. There is some suspicion that we have not yet developed the physics necessary to fully understand the Sun, where strong magnetic fields are erupting and plasmas swirl at ultra-high temperatures. Certainly it is impossible to simulate these conditions in experiments on Earth.

Research to improve solar forecasting is occurring in two major areas. The first area is the correlation of observable phenomena with effects on Earth. For example, we have observed a strong correlation between sunspot cycles and disturbances on Earth. However, this correlation is very coarse; we know that during a certain period of years there will be high levels of solar activity and the accompanying disturbances on Earth. But we cannot accurately predict these disturbances as happening over specific days or hours, as we would like to be able to. Many researchers are trying to refine the correlations between observable symptoms, like increased radio emission, and subsequent eruptions of mass. Some of the best correlations yet are those that have been found between the evolution of sunspot groups and eruptions.

The second area of work is that of constructing a model for the Solar-Terrestrial environment. In addition to the complexities of MHD, the problem is difficult because there are three different domains involved, which all couple together. The first domain is that of the Sun; to simply construct a mathematical model of the Sun is far beyond us at the present time. There are still many mysteries about what is going on inside the Sun, what triggers flares and even why sunspots form. The second domain is the interplanetary medium, once thought of as empty space. This space is filled with the solar wind plasma, which is not fully understood. The third domain is the geomagnetosphere, with its many regions and currents. The magnetotail, extending for millions of kilometers out from Earth, has been difficult to study directly and remains poorly understood. Another complication is that these three domains are not at all separate. A change in one of these domains can have major consequences on the surface of Earth; we hope one day to have a comprehensive model for the entire solar-terrestrial environment but this is certainly a problem for physicists of the future.

Despite these difficulties, some advances in non-comprehensive modeling have occurred, to include development of a large-scale, physics-based heliospheric prediction tool known as the WSA-Enlil model. This model can help provide 1 to 4 days advance notice of solar wind speed and density changes, and when submitted by forecasters to include calculated parameters of CME analysis, aids tremendously in determination of whether a CME may be Earth-directed, and if so, provide timing solutions. Another model, known as the geospace model, provides short-term guidance of the Earth's magnetospheric state using real-time solar wind data and 10.7cm solar flux as inputs to provide a 15 to 45 minute forecast of the possible state of the geomagnetosphere. This model provides another tool to help make decisions regarding the overall planetary geomagnetic response state - perhaps assisting forecasters with warning issuance decisions.

Forecasters will continue to make space weather forecasts based on our present knowledge of the Sun and the Earth's magnetosphere, using all available observation data and model prediction tools as sources for their decision-making. Forecasting accuracy will continue to improve as additional advances in heliosphereic science continues and more reliable models come into operation. The physics of the solar-terresrtial environment is still one of the great frontiers; awating new generations of scientists, more modeling advances, and greater understanding of solar physics.

## Problems and Questions

1. Estimate the radius of curvature of the path of a solar wind proton when it encounters the geomagnetic field. Assume that the proton is moving perpendicular to the field at 400 km/s and the field has a strength of about $10^{-7}$ tesla). What is the motion of the proton like if there is a component of velocity along the field lines?
2. Explain the processes by which solar activity can lead to induced currents in conductors on Earth.
3. What is magnetic reconnection and why is it significant in how the Sun can affect Earth?
4. How are low-orbiting Earth satellites affected by solar disturbances? What about high-orbiting satellites?
5. What is magnetohydrodynamics and how is it used to help us understand the solar-terrestrial environment?