II. SOLAR-TERRESTRIAL INTERACTIONS

A. The Role of the Sun

The Sun is the dominant source of life-sustaining energy to the Earth. We think of its output as constant, but it is not, and even small variations in solar properties can have far-reaching effects on the Earth. The two basic means by which the Sun controls the terrestrial environment are the solar electromagnetic radiation and the solar wind.

The amount of solar radiant energy of all wavelengths received per unit time at the surface of the Earth, the solar constant (1353 watts/m^2), has enormous implications for the terrestrial environment from the outer reaches of the magnetosphere down to the Earth's surface. Ultimately, it is solar radiation that is the basic energy source driving the circulations of the Earth's atmosphere and oceans. Solar radiation is responsible for the ionization of the Earth's upper atmosphere to form the ionosphere, which is important to our understanding of the magnetosphere and its interaction with the solar wind.

The solar wind, which is the continuous (but not steady) flow of the Sun's coronal plasma and magnetic field into interplanetary space, plays both an active and passive role in its interaction with the Earth's environment. In the active mode the solar wind itself causes the final result: the deformation of the Earth's magnetic field to form the magnetosphere, and the recurrent modification of the magnetospheric structure which results in geomagnetic storms. Historically, recurrent (with the 27-day solar rotation period) geomagnetic storms were assumed to originate in hypothetical "M" (or magnetic) regions on the Sun. Only recently have these M regions been identified as coronal holes, large regions of predominantly open unipolar magnetic fields from which high-speed solar-wind streams flow. Because coronal holes have lifetimes of many solar rotations, the plasma flows emanating from them can perturb the Earth's magnetosphere cyclically over a period of many months.

In its passive role, the solar wind acts as a medium through which the Sun influences the Earth in a manner not possible without a pre-existing solar wind. Examples of this are the propagation of hydromagnetic shock waves, the channeling of flare-generated relativistic protons along the curved paths of the interplanetary magnetic field, and the modulation of the galactic cosmic ray flux received at the Earth.

Essential Solar Investigations

1. The Solar Constant

With the potential of today's technology for measuring the solar constant to an accuracy of a few tenths of a percent, the time is right to undertake a long-term program of space-based observations to measure accurately the complete solar spectral irradiance over the 22-year solar cycle. Space, as opposed to ground-based, observations are essential to eliminate the effects of atmospheric absorption, particularly in the important ultraviolet wavelengths. Even more importantly, the observation program should determine temporal fluctuations in particular solar spectral bands. The possible existence of large time-scale variations remains plausible because of our lack of conclusive understanding of the thermonuclear processes in the solar interior, as seen, for example, in the disparity between the predicted and observed solar neutrino flux. In addition, direct observations have provided recent evidence for short time-scale fluctuations, particularly in the EUV where there may be variations as large as 50 percent below 1600 Å depending on the level of solar activity.

For ionospheric and atmospheric physics, the far-reaching implications of these variations in the solar constant underscore the necessity for sophisticated instrumentation on the Solar-Terrestrial Observatory which would measure the solar spectral irradiance over the complete spectrum for the integrated solar disk as well as for selected active regions. Selected instrumentation would also permit observation of spectral bands of particular interest, such as the 1200 to 3000 Å region which includes the Lyman alpha absorption important to the D region of the atmosphere. The spectral irradiance at X-ray wavelengths is also of interest, particularly its variation during solar flares and its correlation with increased ionization levels in the ionosphere.

2. The Solar Wind

A complete description of the solar wind necessitates measurements of particle densities, temperatures, flow velocities, and the vector magnetic field throughout the region from the solar corona to the Earth and beyond. Such a program would certainly involve in situ measurements of these quantities from satellites outside the magnetosphere. Yet, the "initial conditions" for the solar wind are provided by the Sun's corona, and thus our descriptive models of the solar wind will depend on how well we know these initial conditions. The corona is observed best from space where we can measure the coronal X-radiation and where the outer corona can be observed without waiting for a solar eclipse. A particular objective for space-based solar-wind observations would be the study of the formation and evolution of coronal holes and their relation to active region development and decay over the 22-year solar cycle. Since the coronal holes cause conditions in the solar wind which, in turn, cause geomagnetic storms, a study of their development characteristics could lead to the capability of predicting the geomagnetic storms for periods of months in advance. Soft X-ray telescope observations would yield the spatial extent and configuration of coronal holes as well as densities in surrounding regions while the hole is on the visible disk. For densities and magnetic field geometry within the hole region out to a few solar radii, coronagraph limb observations would be made. Magnetograph data would provide information on the three-dimensional magnetic field configuration in and around coronal holes as well as normalized intensity magnitudes.

3. Solar Flares

Both the solar constant and the solar wind are frequently subjected to extreme perturbations over a short time scale as a consequence of the eruption of solar flares in which 10^{25} joules of energy are released, with resulting extreme effects on the terrestrial environment. Solar flares of significant size produce increased X- and ultraviolet radiation, with subsequent increases in the D layer ionization that produce communications interference. During large flare events, such as in August 1972, current surges induced by the magnetospheric response to the flare have caused power disruptions across the northern United States and Canada. During a flare, plasma clouds are ejected by the Sun which impinge on the magnetosphere, producing large, impulsive geomagnetic storms. There are occasional flares which produce GeV energetic particles (solar cosmic ray flares) and MeV particles (called proton flares) which represent serious radiation hazards for manned spacecraft.

Because of the extreme effects of solar flares on the Earth's environment, a program for the prediction of the occurrence and magnitude of solar flares would be a vital part of a Solar-Terrestrial Observatory. Of particular interest in such a program would be the identification of flare precursors, the flare-triggering mechanism(s) and the acceleration mechanisms for electrons, protons, and heavier nuclei. A flare-alert system is a necessity for astronaut protection on the Space Station, particularly when it will be in geosynchronous orbit. Because of its relevance to the Space Station and to solar-terrestrial relations, this flare-alert system would be a natural component of the Solar-Terrestrial Observatory.

B. The Role of the Magnetosphere

As pointed out in the previous section, the solar wind exists continuously as a supersonic flow of magnetized plasma in which the magnetic field strength and flow velocity are significantly intensified in association with coronal holes. If one could turn off the solar wind, the geomagnetic field would revert essentially to that of a large subterranean bar magnet (or a dipole field). This pristine geomagnetic field would be filled with a plasma or ionized gas as an extension of the solar-ionized upper atmosphere, or ionosphere. Tidal dynamo effects would give rise to some circulatory motion of the geomagnetic plasma in addition to its general tendency to rotate with the Earth. However, no spectacular geophysical effects would be expected to result from this magnetized plasma under the conditions of dynamical equilibrium which would soon be established. The situation as it actually exists with the constant flow of the solar wind is quite different.

The magnetized plasma of the solar wind cannot penetrate closer to the Earth than approximately 10 R_E under normal circumstances because of deflection by the geomagnetic field. In the process of its diversion around the geomagnetic field the solar-wind plasma sets up a current system which tends to confine the geomagnetic field to a comet-shaped region or cavity known as the magnetosphere. The average power incident on this cavity due to the solar wind is $\sim 10^{13}$ watts. If this energy were completely excluded from the cavity, then variations in the strength of the solar wind would only change the size of the cavity; the cavity itself would extend only to about the lunar orbit, the circulation of the geomagnetic (or magnetospheric) plasma would still be dominated by the Earth's rotation and atmospheric tidal effects, and there would be no intermingling of solar-wind plasma and terrestrial plasma. Experiments conducted over the past few decades have established, on the contrary, that the magnetosphere has a long tail (several hundred R_E or more), that a strong circulation of plasma occurs—driven in some way by the solar wind, and that the solar wind is a major source of some of the magnetospheric plasma populations. The processes by which momentum, energy, and plasma carried by the solar wind gain access into the magnetosphere have not been identified. However, we do know that the solar wind magnetic field, which carries only approximately 1 percent of the total solar-wind energy, acts as a trigger, or modulator, which determines by its direction what fraction of the solar-wind power is coupled into the magnetosphere.

Gusts of the solar wind in which the embedded magnetic field is directed southward, or antiparallel to the Earth's magnetic field, result in the occurrence of magnetospheric substorms. During an individual substorm lasting approximately 1 hour, a total energy of $\sim 8 \times 10^{14}$ joules is dissipated in the high-latitude upper atmosphere. This dissipation, which is about equal to the total energy of a magnitude 6.7 earthquake, is absorbed almost totally at altitudes near and above 100 km. About half of the energy input is due to precipitation of magnetospheric particles, with the other half resulting from heating by ionospheric currents.

The key outstanding questions concerning substorms include the identification of the physical processes responsible for the triggering of substorm events; the acceleration and precipitation of magnetospheric particles; and the generation of large-scale current systems in the magnetosphere. We must, then, understand how solar-wind influences are transferred into the magnetosphere and how magnetospheric energy is dissipated in the upper atmosphere, and we must look further into possible mechanisms which may couple this energy downward into the stratosphere and troposphere.

The total energy dissipated in a large substorm is comparable to the total energy involved in certain large, low-pressure systems which are observed to develop in the Gulf of Alaska. Both phenomena have been statistically correlated with changes in the large-scale structure of the solar-wind magnetic field. It has also been pointed out that the angular momentum involved in the circulation of plasma at ionospheric heights is sufficient to account for these storm systems provided an efficient coupling mechanism (e.g., viscous effects or planetary waves) is available. Such coupling phenomena are potentially of great significance in our study of solar-terrestrial effects, particularly since a large number of statistical correlations between solar activity and various meteorological phenomena have been identified.

Quite apart from the substorm process itself, another important energy source for the high-latitude upper atmosphere is the large flux of energetic solar protons produced by some solar flares. These protons have direct access to the polar caps within hours after the occurrence of a solar flare. Although the total power dissipated in the Earth's atmosphere during a flare is less than that associated with substorms ($\sim 10^9$ watts), the 1 to 100 MeV solar-flare protons penetrate into the stratosphere and down to the tropopause, where significant ionization is produced. This ionization could form nucleation centers for cloud formation or, as occurred in the August 1972 solar particle event, could result in a significant decrease in stratospheric ozone. In either case an altered thermal balance would be expected, and this could act as a trigger for other meteorological changes at lower altitudes.

Essential Magnetospheric Investigations

1. Charged Particle Energization and Transport within the Magnetosphere

Of the total energy dissipated in the upper atmosphere by the magnetosphere, roughly one-half is carried by energetic charged particles. Therefore, the mechanisms which accelerate the magnetospheric particles and cause them to be scattered into the atmosphere must be identified if this important aspect of solar-terrestrial interactions and its implications are to be understood. The available data from passive measurements are sparse enough to be consistent with a variety of proposed mechanisms. Now needed are active experiments conducted during varied geomagnetic conditions in which particle beams with known characteristics are injected into the magnetosphere and observed as they undergo the processes of acceleration and precipitation. The techniques and instrumentation required for definitive studies will be well developed on Spacelab missions and, hence, will be available for a manned Space Station application. In addition to particle accelerators, the required instrumentation will include visible and UV imagers for remote detection of the beams as they strike the atmosphere, and subsatellites equipped with particle and wave detectors for direct measurement of the beams. The proposed acceleration mechanisms include low-altitude processes and processes in the equatorial plane, near and beyond geosynchronous orbit. It is important, then, that these investigations be carried out in low-altitude orbit and at geosynchronous orbit.

In addition to mechanisms which act to accelerate particles, other mechanisms appear simply to change the direction of energetic particles, scattering them out of their trapped orbits and into the atmosphere. It is thought that interactions between particles and plasma waves are responsible for this scattering. These interactions are expected to be strongest near the equatorial plane and to depend critically on certain parameters such as the local ion density. Definitive experiments in this area can be carried out from the Solar-Terrestrial Observatory at geosynchronous orbit with the capability to release gases, such as lithium or barium, which alter the local ion density. By measuring simultaneously the particle and wave characteristics in the region of the release, a number of proposed mechanisms would be tested definitively for the first time.

While the processes of charged-particle energization and transport operate at all times in the magnetosphere, they are intensified significantly during substorms. A full understanding of the role of these processes in the Earth's environment requires that we identify the substorm triggering mechanism. At present we know that large substorms are triggered with a high probability when the solar-wind magnetic field has a southward component. In the magnetosphere, strong plasma flows have been observed in the nightside equatorial plane, causing attention to be focused on that region for the identification of possible unstable plasma processes as the substorm trigger. Simultaneously there occur widespread and dynamic displays of the aurora, produced by charged-particle bombardment of the atmosphere and resulting in significant atmospheric heating and increased ionospheric conductivity. These low-altitude effects have led to further suggestions that substorms are initiated there in regions of high conductivity. A low-altitude Solar-Terrestrial Observatory could provide definitive tests of such theories by controlled active stimulations of the ionosphere using particle accelerators and gas releases. An observatory at geosynchronous orbit would have the ability to obtain global images of the aurora, thereby identifying the time and location of the first signs of a substorm. Combining this information with simultaneous observations of the plasma flows and active probing in the equatorial plane would give a comprehensive picture of the substorm, the basic disturbance mechanism of the magnetosphere.

2. Transfer of Energy through the Magnetosphere into the Upper Atmosphere

The transfer of energy from the magnetosphere to the upper atmosphere by charged particles, electric fields, and currents occurs predominantly along magnetic field lines. Our understanding of these energy-transfer processes is limited by our lack of knowledge of field-line configuration and by our present inability to measure simultaneously the energy input to the magnetosphere, its flow along field lines, and the effects produced in the upper atmosphere. It is expected that these limitations could be overcome by a properly equipped Solar-Terrestrial Observatory.

The difficulty in determining magnetic field-line configuration lies in the dynamic effects which occur during substorms. During substorm times, a given magnetic field-line configuration can change from an equatorial crossing point of 6 R_E to a crossing at 10 to 20 R_E. Magnetic field lines can be traced both from low-altitude orbits where ion beams can be injected and optically tracked, and from geosynchronous orbit where particle beams can be fired down the field lines into the atmosphere where their interactions can be observed.

With the ability to map magnetic field lines under varying conditions, the Solar-Terrestrial Observatory could then be utilized to investigate the overall problem of magnetospheric-atmospheric energy transfer. Through remote-sensing measurements of solar and solar-wind phenomena conducted from the observatory itself, coupled with possible direct real-time probing of the solar wind by a companion satellite in the interplanetary medium, one could measure the particle and field energy incident on the magnetosphere as well as the solar electromagnetic energy incident upon the atmosphere. Then, by tracing field lines and measuring directly the fluxes of particles and the intensities of magnetospheric currents and electric fields from the orbiting observatory and its companion subsatellites, the flow of solar energy through the magnetosphere could be monitored. The atmospheric response to this magnetospheric energy input would be measured through the optical remote-sensing capability of the observatory.

This combination of techniques would give the broad picture of how plasma and wave energy is coupled from the Sun through the magnetosphere into the atmosphere where it contributes to atmospheric motions.

3. Magnetospheric Effects on the Stratosphere and Troposphere

The magnetic field lines from the Earth's polar cap continue into the region of the solar wind and so provide direct paths for energetic solar-flare protons to follow into the atmosphere. As mentioned previously, these 1 to 100 MeV protons penetrate the entire stratosphere where they may act to reduce the ozone levels significantly, hence upsetting the thermal balance of the atmosphere. From a Solar-Terrestrial Observatory in low Earth orbit one could measure directly the fluxes of energetic protons while monitoring simultaneously the concentrations of minor constituents, such as ozone, in the stratosphere. The remote measurement of stratospheric constituents could be accomplished using a comprehensive set of optical instruments covering the wavelength range from ultraviolet to infrared. These systems generally must have large apertures and optics, and in some cases must be cryogenically cooled. An effective program of this type will, therefore, require a large, versatile facility such as a manned Space Station whose long-duration missions will assure that the correct instruments will be in orbit when an event occurs.

In addition to the effects of solar-flare protons, changes in the large-scale structure of the solar-wind magnetic field (the sector structure) are accompanied by increased levels of magnetospheric activity and by intensifications of high-latitude atmospheric disturbances as measured by atmospheric vorticity indices. The energy dissipated in the upper atmosphere during substorms and the angular momentum carried by the circulating plasma in the ionosphere may, then, play key roles in the dynamics of the high-latitude troposphere.

The next step beyond the statistical correlations made to date would be to investigate possible mechanisms by which this energy and angular momentum are coupled downward through the stratosphere and into the troposphere. The role of a Solar-Terrestrial Observatory could be central to our eventual understanding of how magnetospheric energy may be coupled into the troposphere, affecting ultimately the weather and climate on a global scale. Needed are global measurements of cloud cover, coupled with altitude scans of atmospheric winds, vorticity, composition, and temperature from the 100-km level down to the troposphere. When combined with simultaneous observations of solar and magnetospheric energy inputs, these observations could provide definitive tests of mechanisms through which magnetospheric energy is coupled to low-altitude weather patterns.

C. The Role of the Atmosphere

Lying closest to the Earth and comprising a major part of what we visualize as our environment is the atmosphere. The atmosphere is a dynamic system consisting of several interactive layers: the troposphere where weather systems are found, the stratosphere where the Sun's ultraviolet radiation is absorbed, and, finally, the mesosphere and thermosphere where ionized atmospheric gas provides a basic link in worldwide communications. The characteristics of the atmospheric system are determined by a complex balance of energy inputs from the Sun, the magnetosphere, and the Earth as well as constant exchange of materials with the Earth's surface.

Despite an ever-increasing body of evidence correlating variations in the atmosphere (particularly weather and climate changes) with variations in the Sun, man has been unable to confirm specific physical processes which link the two directly, primarily because of the immense complexity and delicate characteristics of the atmospheric system. The correlations are nonetheless compelling, as, for example, the predictions based on solar cycle variations of droughts in the high plains areas of the United States in the mid-1970's. It appears that changes in the solar character trigger changes in the dynamics of the atmosphere both on a short-term basis, as in the case of individual geomagnetic storm effects lasting for days, and over the long-term sunspot cycle of 11 and 22 years. Even longer period changes have been observed, as in the case of the so-called Maunder Minimum, a period of some 70 years in the late 17th century. During this time, there existed a dramatic minimum in solar activity which has been correlated with the coldest excursion of the "Little Ice Age" in Europe and a concurrent drought period in the American Southwest.

Observations of tropospheric weather phenomena have been vastly improved with better descriptions of the global wave patterns (particularly over ocean areas) through the use of satellite pictures of cloud patterns. However, we currently have no better picture of what is to transpire in weather patterns than the 2-day forecast using predictability schemes developed in the 1940's and 50's. We must study the atmosphere globally in a unified manner, measuring chemistry and dynamics simultaneously. This approach combined with the observation of changing solar and magnetospheric energy inputs should begin to fill out our uncertainties and expose clues to the physical processes which are responsible for solar-related atmospheric changes.

The fragile nature of the atmosphere has been emphasized in the recent concern over the effects of minor constituents (a few parts per million) on the overall conditions in the stratosphere. A push to quantify the detrimental effects of freon has raised more questions than it has answered, primarily relating to the dynamics of the atmosphere and the degree to which other potentially harmful minor constituents are being added to and mixed within its different layers: the troposphere, stratosphere, mesosphere, and thermosphere.

Atmospheric dynamics consisting of winds as well as diffusion processes and the basic chemistry and energetics resulting from solar and magnetospheric influences are again the necessary parameters to be measured. These measurements would provide the knowledge necessary to model pollutant effects in advance, with the ultimate hope of carefully controlling our interaction with our atmosphere.

Essential Atmospheric Investigations

1. Global Atmospheric Chemistry and Dynamics

A fundamental element of the atmosphere which is common to all of the specific investigations is a knowledge of global atmospheric chemistry and dynamics. Techniques are being developed today for use on short-duration Spacelab flights of the early 1980's which will allow the measurement of atmospheric composition, temperature, and winds as a function of altitude throughout the different layers of the atmosphere. The early Spacelab flights will be ideal opportunities to develop the instrumental and experimental techniques and, as such, are a natural lead-in to long-duration Space Station operation. Atmospheric dynamics studies require the long observing times. We are concerned with not only diurnal effects, but with seasonal variations as well as longer term changes over periods of years (e.g., variations with the solar cycle).

Studies in atmospheric chemistry and dynamics would be conducted initially from low Earth orbit, preferably at an inclination high enough to give global coverage. These studies would utilize the comprehensive nature of the instrumentation on the Solar-Terrestrial Observatory, including the complete active and passive remote-sensing capability for the atmosphere in addition to simultaneously monitoring the solar electromagnetic output (the solar constant) and the input of energy from the magnetosphere through particle precipitation and joule heating. Passive plasma and wave measurements would be needed both from the observatory and from subsatellite packages which would transmit information back to the observatory.

The opportunity to place the Solar-Terrestrial Observatory in geosynchronous orbit opens a completely new capability. Whereas the low Earth orbit offers the unique capability to gather detailed height distributions of atmospheric parameters, global averages of the integrated system could be accomplished from geosynchronous orbit. From geosynchronous orbit the atmosphere could be viewed over an entire hemisphere, with the potential to scan compositions, temperatures, and wind characteristics over a large portion of the globe simultaneously. Experiments in this orbit would require new techniques which could be developed in Shuttle-Spacelab flights.

2. Atmospheric Response to Solar Changes

Although this topic is a part of the overall study of atmospheric dynamics which is mentioned above, its importance to Sun-weather studies and environmental change prediction is sufficiently compelling to justify separate discussion. This body of investigations would be directed toward understanding the response of the atmosphere, particularly the troposphere and stratosphere, to both short- and long-term changes in solar parameters combined with the concomitant magnetospheric changes. In particular, the atmospheric response to substorms (periods of hours), large geomagnetic storms (periods of days), solar rotation (27 days), and solar-cycle variations (periods of years) would be studied.

An approach to this investigation would include the continuous monitoring of solar electromagnetic outputs, coronal hole development, solar-wind variations, and magnetospheric substorm and storm conditions, with the careful remote sensing of atmospheric changes. In these investigations, one would try to separate and identify the effects of different inputs — the solar constant, the magnetospheric particle precipitation, the magnetospheric joule heating — in all levels of the atmosphere, with particular attention paid to the troposphere and stratosphere.

By measuring tropospheric response to these varying inputs, we should be able to postulate coupling mechanisms which could then be tested with a more specific set of experiments. We must invest in this type of activity if we are ever to reap the rewards associated with long- and short-range weather prediction.

3. Stratospheric Maintenance

As in the previous section, this topic is also a part of the overall atmospheric chemistry and dynamics problem which, because of its importance, must be addressed separately. The thrust of the investigation centers around understanding the processes that control and maintain the stratosphere, which is of basic importance as an ultraviolet shield. The stratosphere is affected by solar, magnetospheric, natural terrestrial, and man-made inputs. These inputs need to be separated and their effects quantified in order that adequate stratospheric maintenance can be assured through whatever protective measures are necessary.

The Sun can affect the stratosphere directly through the variation of solar electromagnetic radiation, particularly in the EUV wavelengths, and through the generation of high-energy protons which can penetrate the atmosphere down to stratospheric levels. These particle events (polar cap absorption) have been observed to modify ozone concentrations during large magnetic storms. The Sun, through the magnetospheric filter, can affect the stratosphere in other ways. For example, changes in coronal hole structures can change the solar-wind parameters which, in turn, can cause magnetic storms in which particle acceleration and precipitation into the atmosphere are intensified. This precipitation can modify the thermosphere drastically and produce NO, which if transported to stratospheric heights could have a significant effect on ozone content. The extent to which NO is produced and transported is currently not known.

Naturally occurring terrestrial events, particularly volcanic eruptions, can inject significant quantities of trace materials into the stratosphere. The injected material can persist for months and years. In addition to the natural inputs, man's manufacturing activities have reached such a level that the effluents are of large enough quantity to affect the stratosphere globally. These effluents must be measured and their effects on the stratosphere quantified.

As in the previous investigations, global remote sensing of the atmosphere both from low Earth orbit and geosynchronous orbit combined with simultaneous observation of solar and magnetospheric energy inputs will hold the key to understanding stratospheric processes.