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**SOLAR AND MAGNETOSPHERIC SCIENCE**

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and Robert D. Chapman*

*Office of Space Science  
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16. Abstract  The current status of the Solar Physics Program and the Magnetospheric Physics Program are discussed in this document. The scientific context for each of the programs is presented, then the current programs and future plans are outlined. The narrative thereby shows how the programs expect to achieve their goal of understanding the solar terrestrial environment.			
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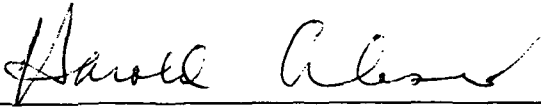
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## PREFACE

The Solar Terrestrial Programs Office was set up by the Office of Space Science within NASA in recognition of the critical need for research directed toward an understanding of the sun and its influence on the planet Earth. The goal of the programs is to understand the generation of energy in the solar interior; to understand how this energy is transported and transformed into phenomena on the sun, in the interplanetary medium, and in the Earth's magnetosphere, ionosphere and atmosphere; and, to understand the processes which couple these phenomena.

From time to time, the office will publish working documents describing the status of scientific research in the discipline it supports, and discussing future plans. This document, by Dr. Adrienne Timothy, the Chief, Solar Physics, Dr. Erwin Schmerling, the Chief, Space Plasma Physics, and Dr. Robert D. Chapman is a summary of the discipline's plans.



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Dr. Harold Glaser, Director  
Solar Terrestrial Programs

# SOLAR AND MAGNETOSPHERIC SCIENCE

by

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*Office of Space Science  
National Aeronautics and Space Administration  
Washington, D.C. 20546*

## STATUS OF SOLAR PHYSICS

### Elements of a Solar Physics Program

*Ground Based Solar Research*—Operationally, Solar Physics may be divided into three major areas: ground based research, space research and theory. Ground based solar research concentrates predominantly on observations of the cooler reaches of the solar atmosphere, from the photosphere to the low chromosphere, because these radiate in wavelengths ranging from the near ultraviolet to the near infrared which reach the ground, and on radio studies of high temperature regions and phenomena, since much of the solar radio emission can also penetrate the earth's atmosphere.

The turbulence of the earth's atmosphere currently limits the resolution of most of the visible light observations to the order of 1-2 arc seconds, although with the more sophisticated telescopes resolutions of the order of 0.5 arc seconds (350 km) may occasionally be obtained during brief periods of "good seeing." With this level of spatial resolution it is possible to resolve the detailed structure of convection cells (the supergranulation and granulation network) on the photosphere (the lowest visible surface of the sun).

In addition to studying the height structure of the lower levels in the solar atmosphere, one of the most important contributions made to solar physics by ground based instruments is the measurement of photospheric magnetic fields. Magnetic fields dominate the structure of the outer solar atmosphere and are considered to be the source of the energy dissipated in flares and other transient events. In the absence of direct measurements of the upper extensions of these fields into the chromosphere and corona—measurements which will be attempted from future space missions—a variety of different mathematic techniques are used to extrapolate the measured photospheric fields to chromospheric and coronal levels.

Another significant contribution made by the ground based observatories is the measurement of velocity fields, which indicate the magnitude and direction of material motions on the solar disc and hence enables the solar circulation and oscillations to be studied. The presence of vertical oscillations

in the chromosphere, of which the 300-second period oscillations predominate, was first discovered from the ground. These oscillations represent a mechanism whereby mechanical energy is transported out of the convection zone just under the solar surface to provide a non-radiative source of heating for the outer solar atmosphere. Investigation of different varieties of wave motion in the solar atmosphere can provide a basic tool whereby substructure conditions may be probed. Evidence of large scale velocity fields is also being sought in the understanding of basic solar convection and conduction.

A final area of ground based research which provides a significant contribution to solar physics is solar radio astronomy. Existing radio facilities can image the corona with about 1 arc minute (42,000 km on the sun) spatial resolution and can detect and follow moving bursts of radio noise (Type II, III and IV) emitted during transient events.

*Solar Space Research*—Solar space programs are complementary to the ground based efforts in that they study those outer extensions of the solar atmosphere that radiate predominantly at short wavelengths which are absorbed by the earth's atmosphere, making them invisible from the ground (Figure 1.)

At increasing heights, the temperature of the solar atmospheric layers increases from chromospheric values (10-50 thousand degrees) to coronal levels (1-2 million degrees). The predominant photons emitted by the layers increase in energy from the ultraviolet to soft X-radiation. Radiation from flares, which are known to be highly energetic phenomena, sometimes extends through the hard X-ray region of the spectrum (10-100 keV) and into the gamma ray region (100 keV-10 MeV).

Measurement of solar radiation in these spectral ranges is important not only as a tool for studying the variation of physical parameters with height in the outer solar atmosphere but also because of the interaction between this radiation and the terrestrial atmosphere. The ultraviolet emission dissociates molecular oxygen in the terrestrial atmosphere providing atoms which react with other molecules resulting in the formation of the ozone layer. Extreme ultraviolet and soft X-ray wavelengths cause photoionization of the neutral constituents at higher levels in the earth's atmosphere, producing the ionosphere. A knowledge of the strength and variability of the solar emission in these wavelengths is thus vital to our understanding of the terrestrial environment and has been a prime contribution of the solar space program.

Many centuries have been devoted to the development of the ground based instruments while only slightly more than a decade has elapsed since the first Orbiting Solar Observatory (OSO) satellite was launched. In this relatively short time period, however, technology has improved to such an extent that the spatial resolution achieved by space borne telescopes already rivals that of the ground based instruments and the spectral resolutions are such that extremely sensitive measurements of material motions in flares, sunspots, and other solar features can already be made.

The measurement of magnetic fields from space presents a more difficult problem, due mainly to the fact that the change in the shape of a spectral line produced by a magnetic field becomes proportionally smaller as the wavelength of the line becomes shorter. This problem is aggravated by the fact that space telescopes have typically smaller collecting areas than their ground based counterparts and the signals collected are smaller. As space transport systems get larger, however, this size restriction will be overcome. There is already significant interest, on behalf of the ground-based solar physics

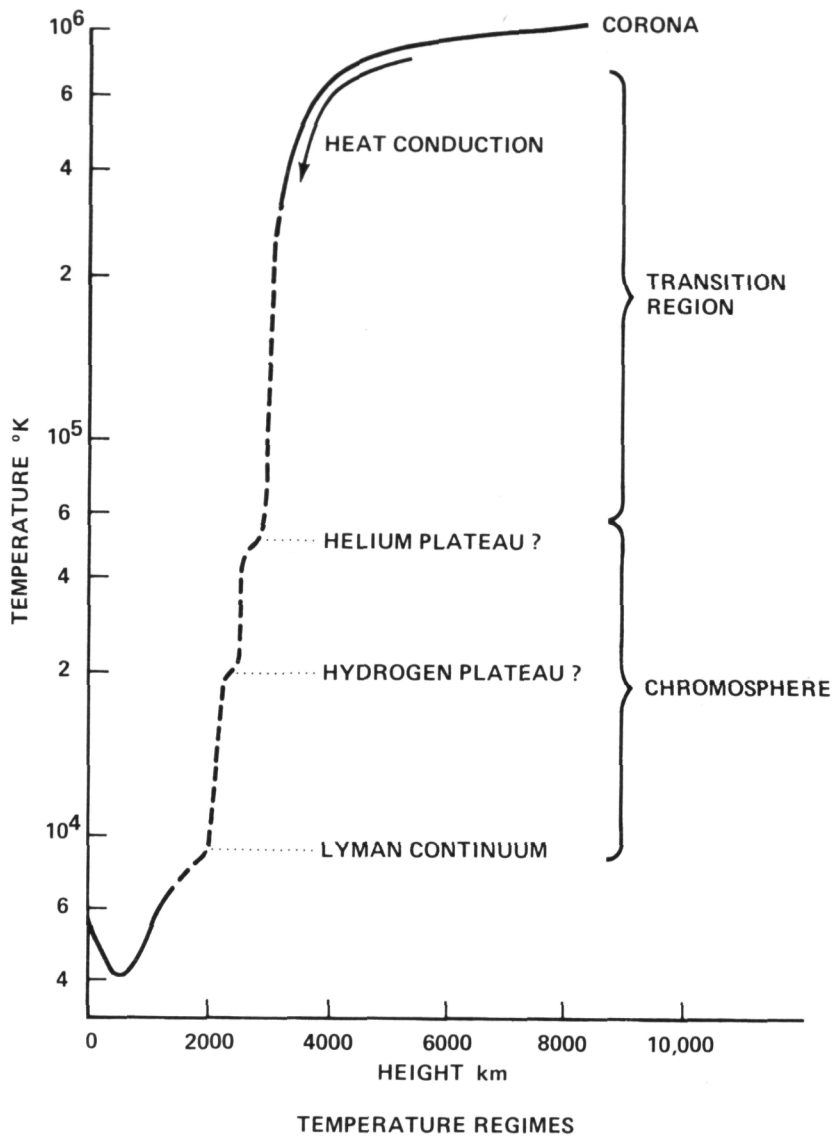


Figure 1. Temperature regimes in the solar atmosphere. The images record radiation that arise in three different levels in the atmosphere.

community, in the possibility of flying large (1 meter diameter) visible light telescopes above the atmosphere so that consistent sub-arc second spatial resolution may be achieved.

Another element of solar space research is the measurement of the solar wind and of solar cosmic rays. A number of missions have already been flown, and more are planned, to study these phenomena and to investigate the interaction of the wind and the cosmic rays with the earth's magnetosphere. In addition, a number of planetary missions carry instruments which enable the variations in these parameters to be studied as a function of distance from the sun.

Responsibility for the United States Solar Space Program has traditionally been shared between NASA, the Department of Defense (USAF/USN) and the National Oceanic and Atmospheric Administration (NOAA). NASA has been predominantly involved in the basic scientific missions while the USAF/USN and NOAA primarily sponsor solar monitoring missions. As in the case of the ground based research programs these space missions are coordinated through ICCA.

A final, necessary, part of the solar program is the theoretical research into solar and stellar structure, convection and circulation theory, magnetohydrodynamics, plasma turbulence, solar wind theory and similar topics.

The bulk of this small, but important, element is conducted in the Universities and is supported by a wide variety of agencies (NASA, NSF, Smithsonian Astrophysical Observatory, ERDA) who once more coordinate through the auspices of ICCA.

### Solar Physics—Major Questions and Major Accomplishments

The questions which still confront the solar physics community may roughly be divided into four major problem areas which have both astronomical and terrestrial applications. These are:

- What is the source of the sun's energy and how stable is it?
- What processes govern solar convection and circulation? How is the solar magnetic field generated? How does the solar cycle work?
- How is the outer atmosphere of the sun heated? What governs the outflow of material into the solar wind?
- What are the physical mechanisms producing flares and other manifestations of solar activity?

There are, as yet, no single studies which can be claimed to have completely solved any of these major problem areas. Each advance, like the discovery of the supergranulation network, the prediction and subsequent verification of the existence of solar wind, or the prediction and verification of flare-produced gamma ray emission, has merely brought us one step farther toward the ultimate solution of these problems.

*What is the Source of the Sun's Energy and How Stable Is It?*—The first major question in solar physics relates to the basic properties of the sun as a star. The popular concept of the solar interior is of a relatively small, and compact, inner core containing approximately half the mass of the sun, but filling only about 1/64 of the total solar volume. Ninety-nine percent of the total solar energy output is generated in this core by fusion of hydrogen nuclei into helium, and mass is devoured in the process at a rate of 5 million tons per second. Beyond the inner core lies a relatively uniform mixture of hydrogen, helium, and heavier elements such as carbon, nitrogen, neon, magnesium, silicon, sulphur, aluminum, calcium, iron and nickel, whose abundance ratios are assumed to be approximately the same as in the earth's crust. These heavier elements were probably formed either in the early moments of the "big bang" universe or in the interior of earlier generations of stars in which the matter existed. Energy generated as gamma ray photons in the core is slowly transported toward the surface by a succession of absorption and re-emission processes by the interior solar gas. Photons become progressively less energetic at each interaction. At approximately 0.86 solar radii from the sun's center, matter becomes very opaque and radiative processes can no longer transport the energy. Turbulent convection takes over at this point. It is in this outer convective layer that a small fraction of the outward flowing

solar energy is converted into convective motions and from thence into the magnetic fields, and into the hydrodynamic and hydromagnetic waves which are the source of all the various manifestations of solar activity and of the solar wind.

It takes approximately 1 million years and an uncountable number of interactions for the radiant energy generated by the central fusion process to finally emerge, in the form of visible light, from the solar surface. Thus observations of the total solar radiative flux output carry little information about the physical characteristics of its source.

In addition to gamma rays, high energy particles, called neutrinos, should be generated during the fusion processes. These particles have the property that they make an almost unobstructed passage through the sun and should be detectable at the earth's surface, thus providing a direct probe into the solar interior.

This picture of the solar interior has a broad base of support. It agrees with most measurements of the physical properties (mass, size, energy output) of the sun and of other, similar stars. However, there is one major problem with the theory, based on one vital, negative measurement.

Sophisticated experiments have failed to detect any neutrinos. This discovery has brought under scrutiny all the relevant physics and astrophysics assumptions made regarding the theory of weak interactions in particle physics, the opacity of the sun, the theory of radiative transfer, circulation and convection theory, and all the elements of basic stellar structure. Abundance ratios have been varied and the distribution of heavy metals in the solar interior has been made nonuniform to try to explain the anomaly but none of the physically acceptable explanations has yet succeeded in reducing the theoretically predicted flux to the observed level. Explanations are now becoming more exotic. It has been proposed that the neutrino may prove to be an unstable particle, or that a black hole may lurk at the center of the sun and may be slowly eating away its core. It is ironic to note that after many centuries of acceptance that the sun is the center of the universe, man now finds it difficult to believe that the sun is anything but a normal, middle-aged star and that such exotic proposals are not greeted with enthusiasm by the scientific community.

Not finding the anticipated neutrino flux has led to some serious re-evaluations of the theory of the solar interior. New methods of searching for neutrinos are currently being proposed, diagnostic techniques are being sought to probe the outer convective envelope, and additional theoretical efforts are being brought to bear on the problem.

Solar terrestrial implications of this entire theoretical structure are important, too. Paleoclimatological studies indicate periodic intervals of major glaciation over the entire planet. Are these periods due to a slow variation in the total solar output (the solar constant)? Might the interior furnace turn off and on with such a long period?

Since approximately 1 million years are required for variations in the internal solar energy production to appear at the surface, and since a ten thousand year lag is expected for changes occurring at the base of the convective zone, it is unlikely that any variations in total solar radiative output could be measured that would "throw light" on the neutrino problem. There are, however, several arguments in favor of such measurements. First, it is known that the earth's climate is extremely sensitive to changes in the solar constant and hence the magnitude of these changes over periods of a solar cycle and longer should be determined. A second argument in favor of such a measurement is that since the

theories of the solar interior are in doubt the estimates of the basic time constants may also be in error. The definite detection of a variation in total solar output, of the order of 1 percent, or of a continuous slow trend in the emission, would provide a new clue to the mystery of the solar interior. It should be noted that in the "black hole theory" the hole is currently assumed to be generating about 50 percent of the total solar emission and should alter the solar energy output significantly on a time scale considerably less than  $10^9$  years. Under such an unlikely circumstance a small change in "solar constant" might indeed be detected.

*What Processes Govern Solar Convection and Circulation? How Does the Solar Cycle Work?*—All the surface features seen on the sun, sunspots, active regions, prominences, bright points, and probably also coronal holes, are the result of solar convection and circulation. The "sunspot cycle," or "solar dynamo," is also the result of these processes and a variety of seemingly satisfactory explanations have been proposed to explain the observed 11 year periodicity in the sunspot number and location, and the 22 year periodicity in the solar, polar magnetic field polarity. Recently, however, evidence has come to light which throws doubts on these theories, or at least indicates that they do not represent the whole story.

In 1610 the telescope was first used for astronomy and sunspots were one of the early discoveries. Sunspots were not at the time considered to have any intrinsic interest; nevertheless, sufficient records were kept for the sunspot cycle to be traceable from that date.

It is perhaps typical of science as a whole that as soon as sunspot observations became technically feasible, the sun exhibited a condition which we today consider to be an anomaly. After it was clearly demonstrated that sunspots exist, the sun underwent a period with almost no activity for an interval not of 2-3 years, as is normally the case, but of approximately 70 years. "Normal" activity was resumed in 1715 and the sun has since exhibited the familiar 11 year cycle, which was recognized in 1843 (Figure 2).

During the 70 years of inactivity only a handful of sunspots were reported. Supporting evidence of the inactivity is found in eclipse reports, which describe the corona to be a uniform, weak glow at this time, and in records which indicate auroral activity was virtually non-existent during this period. It is also of interest to note that this was a time of extreme cold, a mini ice age, in the northern hemisphere.

The occurrence of this 70 year minimum, first reported by Maunder, and called the Maunder minimum, provides strong evidence that the sun must have at least two stable convective modes of circulation, the present "solar cycle" mode and the "Maunder minimum" mode. Since the sun is billions of years old the fact that the "solar cycle" mode has been with us for the past 300 years is no guarantee that this is its "normal" state. We must, therefore, try to understand these modes to determine what warning, if any, there is likely to be of an impending change in mode, to discover the probable variation in solar output and solar wind which might accompany such a change and to understand the possible effects these variations may have on our environment.

Experimentally there have been many ground based and space borne studies of solar surface features. The sunspot cycle has been studied for centuries. Sunspots exhibit a differential rotation rate and rotate faster at the equator than at high latitudes. With the invention of more refined equipment it has been possible to measure the rotation rate of the sun at the photospheric level by looking at the

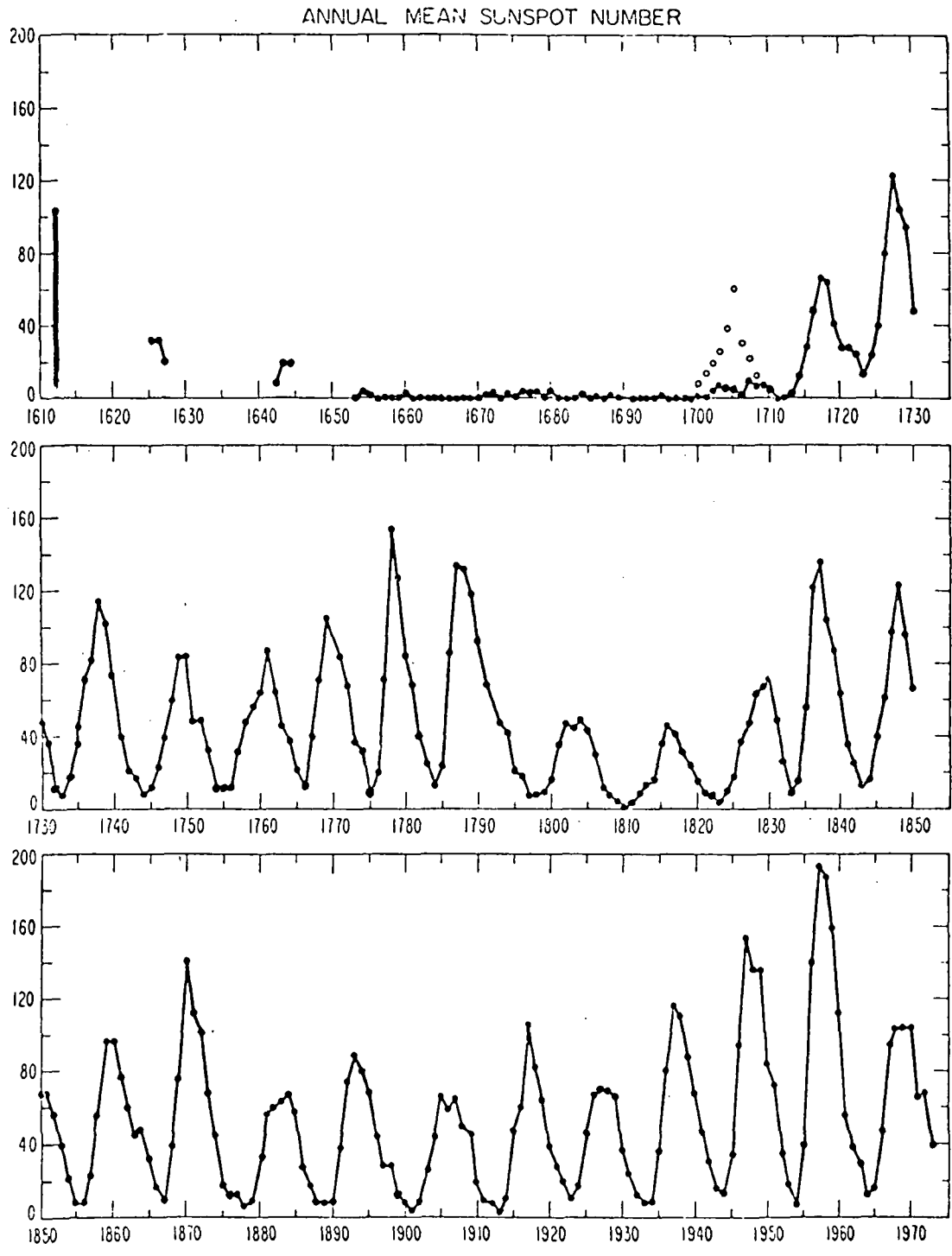


Figure 2. Annual mean sunspot numbers. Numbers before 1700 were inferred from historical records by J. Eddy. Note the long Maunder minimum from 1650 to 1710, when the sunspot number seldom rose above zero.



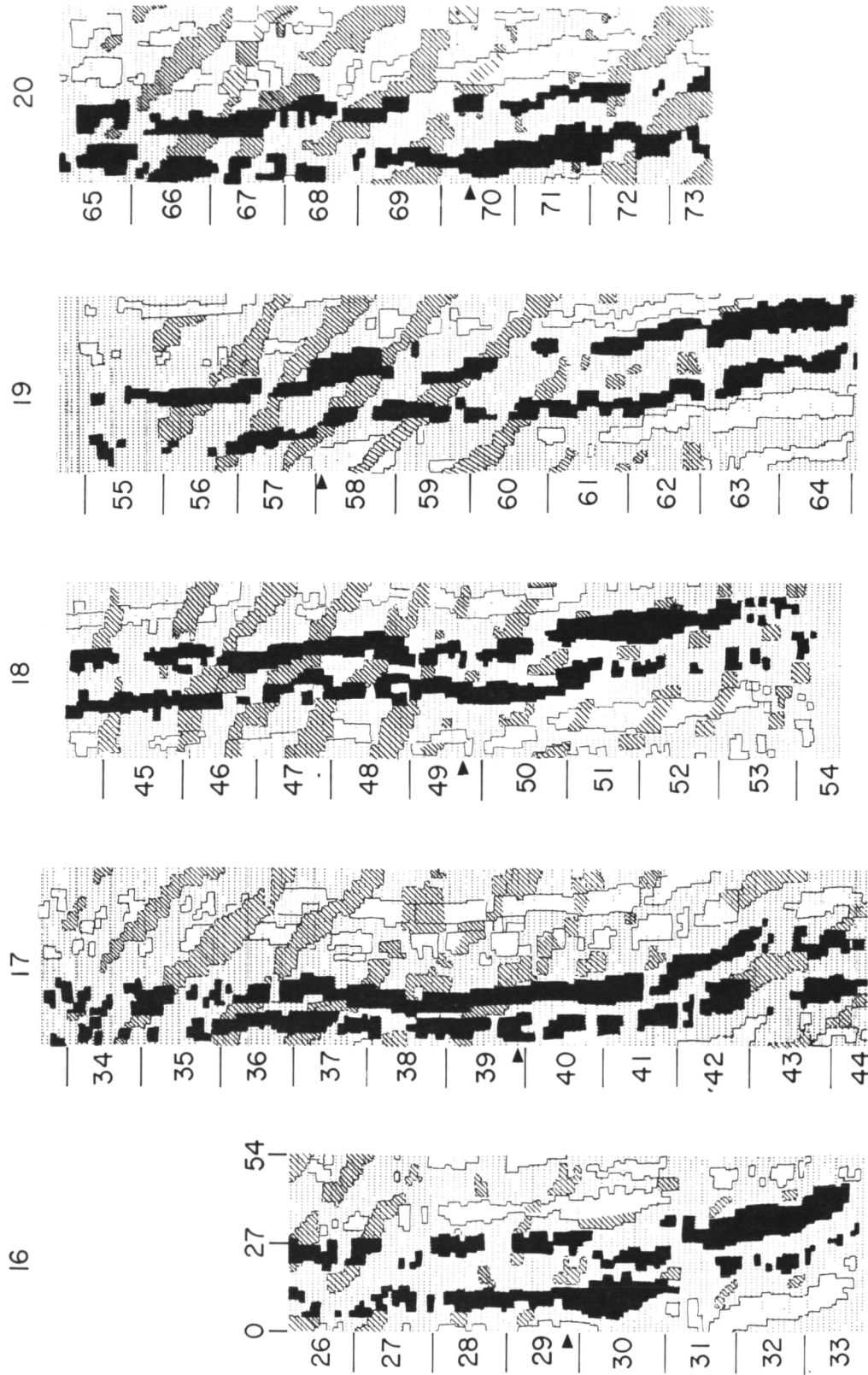
doppler shift of spectral lines. Magnetic field rotation rates have also been studied and the recent Apollo Telescope Mount (ATM) observatory, on Skylab, provided measurements of rotation rate as given by coronal features. Although the measured rates show some scatter, most are consistent with a situation in which the solar equator rotates approximately 50 percent faster than the poles. There are, however, some exceptions to this rule. It was noted several years ago that the magnetic fields display both a differential and a rigid rotation characteristic (Figure 3). Research, sponsored jointly by NASA and the NSF, showed that magnetic sector boundaries in the solar wind display a rigid rotation pattern which has lasted for up to five solar cycles. Finally, the ATM data showed that some coronal holes, which are associated with large scale unipolar field patterns, also display a rigid rotation.

The accomplishments in the area of solar cycle and solar circulation studies to date have been the discovery of these effects; explanations by and large are still lacking. The more rapid rotation of the solar equator has been explained as a consequence of meridional circulation within the convective zone. Such circulation should, in theory, be accompanied by a pole to equator energy flux difference of at least 10 percent. Not only has no such difference been observed but the NSF-supported research in this area indicated that the energy flux is constant with solar latitude to better than 1 part in  $10^3$ . It may be claimed that convection in a stratified atmosphere in which density changes by a factor of  $10^6$  in a distance of  $2 \times 10^5$  km is extremely difficult to treat mathematically. Even so, the discrepancy of 100 in pole to equator flux is difficult to explain.

Two schools of thought currently exist regarding the rigidly rotating features. The first school favors the existence of some deep seated magnetic dipole in the sun whose effect is seen superimposed on that of the differentially rotating "dynamo" field. The second school favors the existence of a variety of different convection-circulation modes, of which one is a rigidly rotating mode and another the dynamo mode. For two modes to co-exist they must be very loosely coupled. Theoretical computations on this problem have been stimulated by the ATM results.

The 11 year time scale of the solar cycle presents yet another problem in convection and circulation theory. The basic model of the solar cycle is that an azimuthal magnetic field, of approximately 100 gauss, situated somewhere beneath the solar surface, is amplified as a consequence of non-uniform rotation over a period of approximately 10 years. It rises to the surface during this time as a result of magnetic buoyancy. Unfortunately, computations of the rate of rise of such fields indicate that they rise to the surface from the base of the convection zone in only 5 years, a time insufficient to explain the amplification and at odds with the observations. Clearly more theoretical effort is required to explain this dilemma.

The very character of magnetic fields observed on the solar surface causes a problem. In theory, fields emerge contorted by convective motions into unstable configurations which must reconnect or dissipate rapidly. The X-ray bright points, discovered by ATM, appear to be excellent examples of this effect and the physical characteristics, lifetimes and typical magnetic field strengths of these features fit well into the theoretical picture. In general, however, the photospheric magnetic fields are less well behaved. High resolution observations of these features show the fields to be compressed not only in the sunspots, where fields of 3000-4500 gauss are common, but also in the quiet sun where the general background field of 1-2 gauss is found to be composed of isolated flux tubes of 2000 gauss compressed to diameters of the order of 400 km. Physically, such a situation is difficult, if not impossible,



26.84 DAYS CALENDAR SYSTEM STARTING FEB 19, 1926

Figure 3. A plot of the inferred solar magnetic structure during sunspot cycles 16 through 20. Sectors with field polarity toward the sun have darkest shading. Note the similarities of the patterns from cycle to cycle.

to explain. More detailed studies of the physical characteristics of sunspots reveal that they are cool at photospheric levels and this could explain their compression. But why are they cool? Since the magnetic fields effectively insulate them from their surroundings spots could equally well be hot!

Theories have been proposed involving the increased production of hydromagnetic waves, and a search for evidence of these waves is clearly necessary. Studies of sunspots currently being conducted by the OSO-8 spacecraft may contribute to the solution of this problem.

The compression of the fields is not the only puzzle. Theoretically it is predicted that a sunspot should split into many smaller spots on a time scale of about an hour and that these should further disintegrate, quickly dispersing the sunspot fields. The reverse is, however, seen to occur. When a sunspot first emerges small spots are seen to amalgamate, and even old spots take considerably longer than an hour to break up. What is the cause of this stability?

It is evident that additional observations are required to determine the height structure, inherent wave motions and the magnitude of internal and neighboring velocity fields in sunspots and flux tubes. Only then can the associated theory progress to a point where the physical mechanisms involved can be determined.

*How is the Outer Atmosphere of the Sun Heated and What Governs the Outflow of Material Into the Solar Wind?*—Although the heating of the outer solar atmosphere and the outflow of energy into the solar wind may be considered part of the general solar convection and circulation problem, it is convenient to consider it separately. Since the discovery of the million degree corona, solar physicists have been trying to determine the physical mechanisms causing the high temperature. Detailed studies of the structure of and the wave motions present in the chromosphere have been possible from the ground for many years. The investigation of the structure of the overlying transition region and corona, and of the energy transport mechanisms present in these regions, has only been possible since the advent of solar space research. Furthermore, it is only with the relatively recent improvements in rocket and satellite pointing capabilities and with the accompanying improvements in the spatial resolution available with space borne instruments, that significant advances have been made in our understanding of these regions (see Figure 1).

The first observational determination of the structure of the steep transition region, which lies between the ten thousand degree chromosphere and the million degree corona, was made from a sounding rocket flown during the 1970 solar eclipse. The first satellite observations of the height structure of the transition region, made at arc minute resolution from the Orbiting Solar Observatory, OSO-4, and half arc minute resolution from OSO-6, enabled some quantitative models to be made of the mean structure of the outer atmosphere of the quiet and active sun and provided estimates of the downward conductive energy flux and the radiated energy flux. These estimates were subsequently shown to be in error when higher resolution observations became available during the ATM mission. With the ATM's 5 arc second spatial resolution the supergranulation structure could be resolved. The ATM extreme ultraviolet data not only proved that conductive and radiative energy fluxes were comparable in both the network center and in its boundaries but also enabled the height structure of the cells to be traced. Contrary to earlier theoretical predictions the boundary was found to remain bright in the EUV lines to a temperature of about 700,000 degrees, at which point the magnetic fields at the network boundaries spread out to fill the cells and the structure could no longer be resolved (Figure 4).



Figure 4. The chromospheric supergranulation structure is seen in this red hydrogen line photograph to be outlined by dark fence-like structures. These are spicules seen against the bright disk.

Ground based studies of the sun have shown that the chromosphere undulates with a period of around 300 seconds. This mode of oscillation has come to be called the 300-second oscillation. It is of great interest as one possible source of atmospheric heating. Therefore, observations have been made to trace the oscillation upward through higher atmospheric layers. It was found that no trace of oscillations remains at heights where the temperatures are greater than about 20,000 degrees, nor are there any other periodic variations in temperature, density or brightness observed. Non-periodic brightenings were, however, detected which might be indicative of upward traveling shock waves although preliminary estimates show that the energy carried by these waves is insufficient to heat the corona. Thus, while the ATM results have contributed significantly to our knowledge of these outer solar layers, they have not, as yet, provided the solution to the basic problem of heating.

The role played by spicules (Figure 5) in the heating process is still undetermined and will probably remain so until it is possible to resolve these features from space and to determine their physical

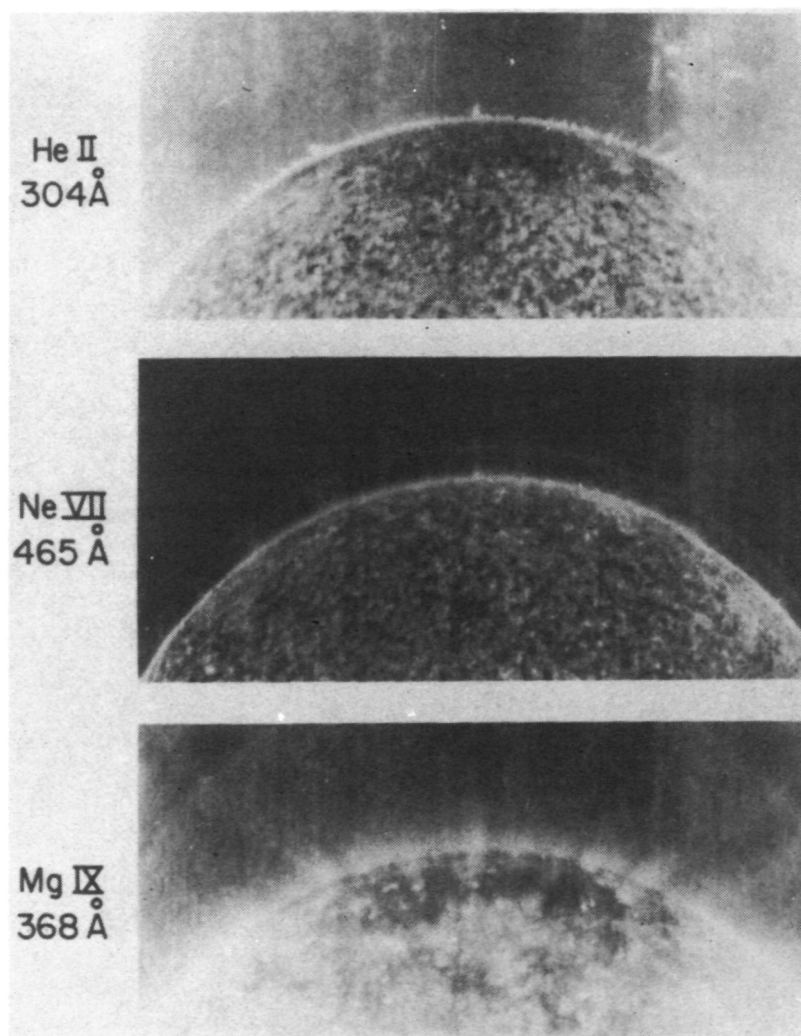


Figure 5. Spicules seen at the solar limb appear bright against the darker background. Photographed by the Naval Research Laboratory instrument on ATM.



composition as a function of time. The possibility that magnetic field instabilities may be the source of the coronal heating has also been proposed and requires significantly more investigation before it can be either verified or refuted.

The situation is similar in the case of the solar wind. The existence of the wind was predicted some years before the advent of space research. Measurements made from space in the early 60's confirmed its existence and revealed the presence of a distinctive structure. Three different types of high velocity stream were recognized (Table 1). The first type was the non-recurrent wing disturbance which could definitely be correlated with flare activity. A second type of non-recurrent wind disturbance was also found, with an energy content approximately one-tenth that of the flare-associated disturbance. The source of this second type remained a mystery until the ATM mission when white light coronagraph measurements revealed the fact that prominence activated coronal transients were the likely source (Figure 6). The third type of wind disturbance, recurrent high velocity streams, were

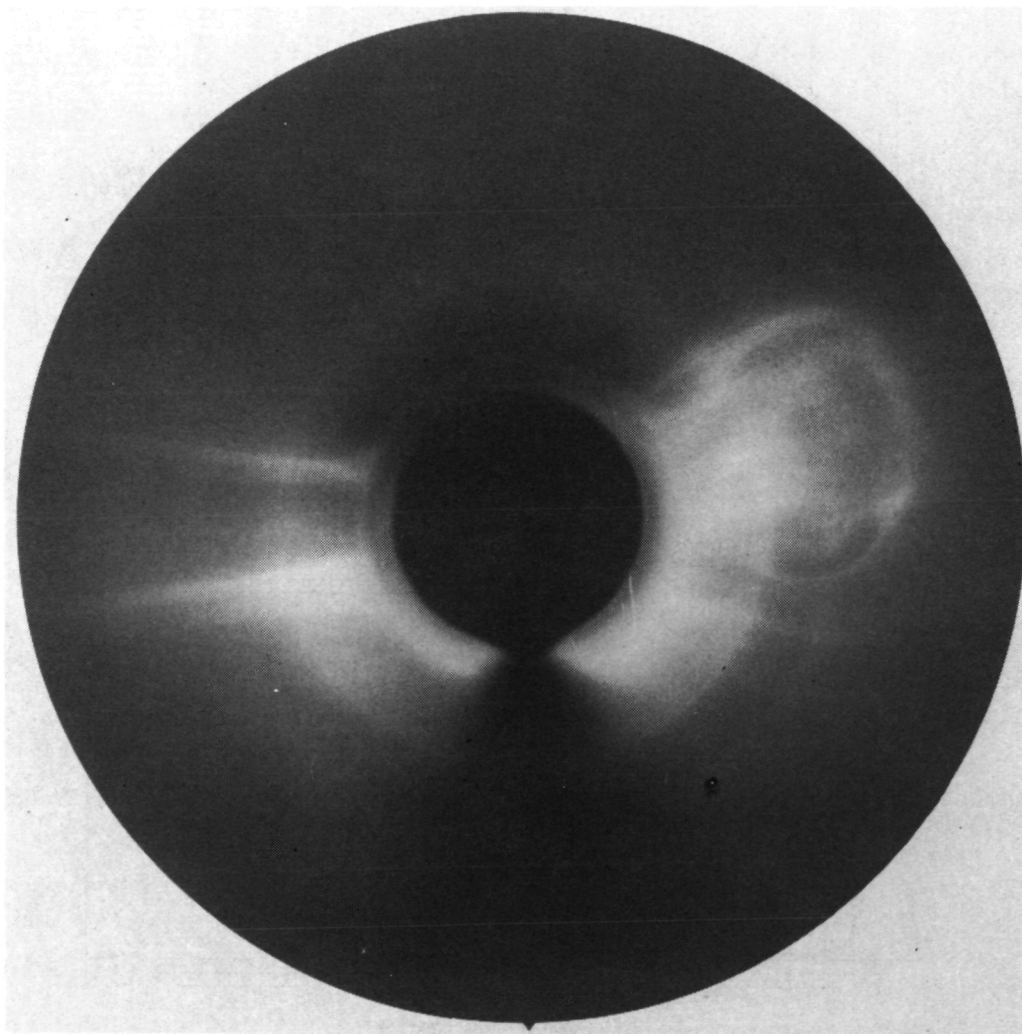


Figure 6. Coronal transient photographed by ATM is a giant bubble rising through the corona. Picture courtesy of the High Altitude Observatory, Boulder, Colorado.

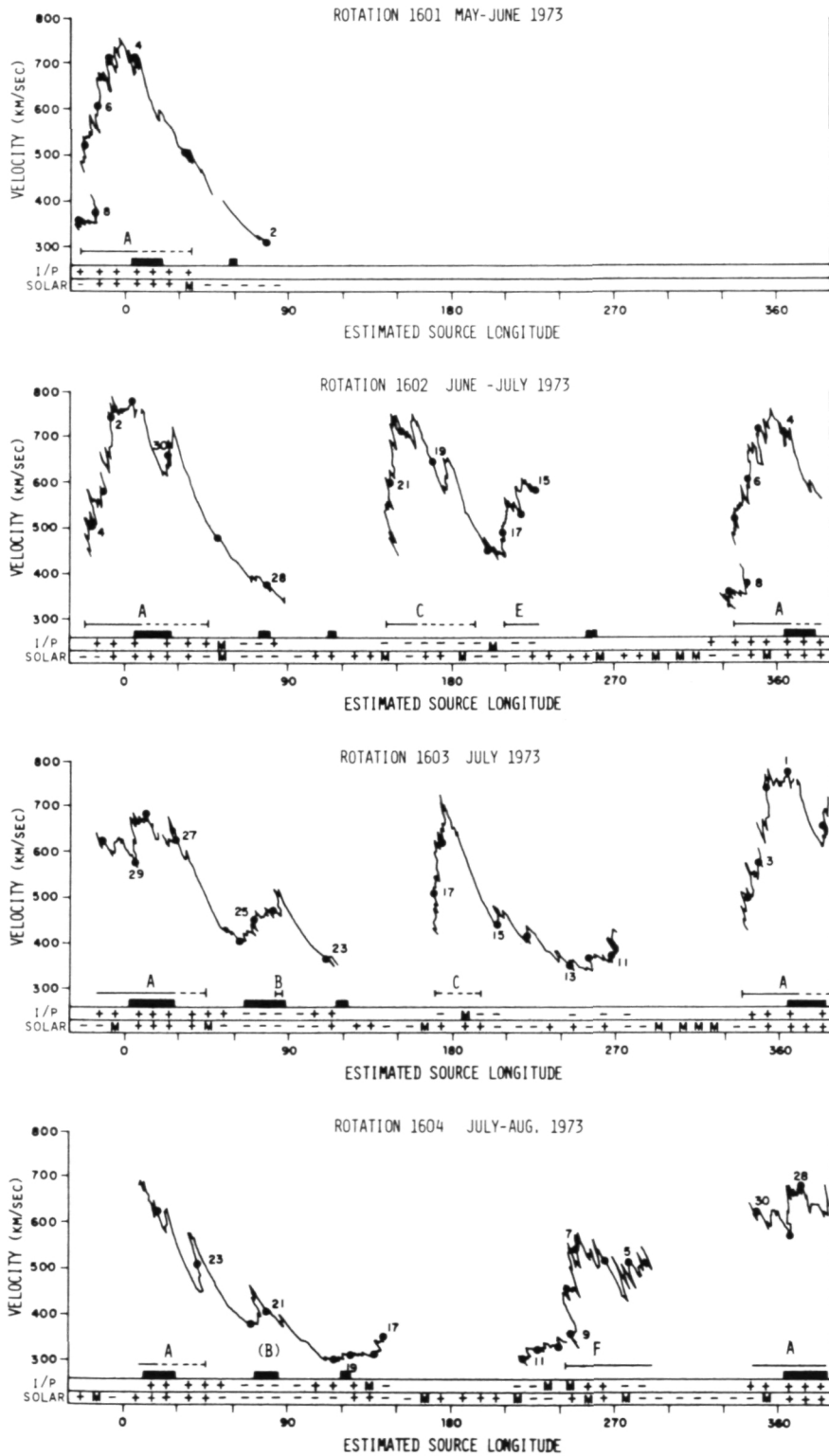


Figure 7. Solar wind velocity plotted as a function of the inferred source longitude on the solar disk. The high velocity streams recur in successive rotations of the sun.

finally associated with coronal holes (cool, open magnetic features) as a result of NASA sponsored sounding rocket and satellite (OSO and ATM) programs (Figure 7).

This last discovery is possibly also the most significant since it indicates that the normal velocity of the solar wind may not be the 300 km/sec value most frequently measured but may be substantially higher. The lower velocity values may merely result from the presence of the activity-associated closed magnetic structures at low latitudes. If this proposal is correct, then a constant high velocity stream should exist at the solar poles, where coronal holes (Figure 8) are invariably observed. In addition, it may be presumed that during the Maunder minimum period, the wind may have flowed at a consistently higher velocity. This fact may again provide a clue to the solar-terrestrial climate interaction problem.

Steps are currently being taken to clarify this question by investigating the basic properties of coronal holes using ATM and OSO-8 data. A series of workshops have also been initiated to provide an integrated attack on the nature of those features. It may, however, prove impossible to resolve the problem without making measurements of the solar wind structure out of the plane of the ecliptic. Such measurements are also planned.

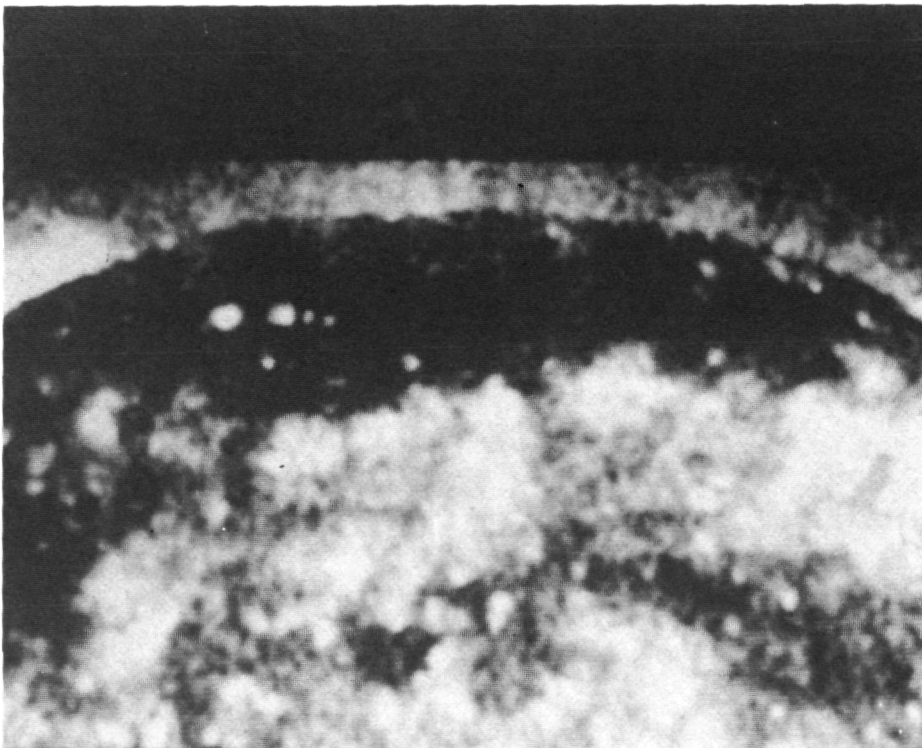


Figure 8. Extreme ultraviolet emission from the sun (Mg X line at 625 Å). The digital data from the Harvard College Observatory instrument on ATM was converted to this black and white image. Small bright points of emission can be seen in the darker coronal hole. The decreased emission in the coronal hole is due to the fact that both density and temperature are lower in the hole than in the surrounding quiet corona.



To date it has proved to be technologically impossible to measure the temperature of the middle and upper corona from which the wind presumably originates. Coronal density and magnetic field configurations are, however, available from white light coronagraph observations (Figure 9). A knowledge of this parameter is vital to our understanding of wind production since most theories show the wind velocity to be a sensitive function of temperature. Recently, new diagnostic techniques have been developed which have the potential of providing coronal temperatures and the first measurements should be made late in this decade.

*What Are the Physical Mechanisms that Produce Flares and Other Manifestations of Solar Activity?*—The very important major problem area confronting solar physicists is that of the nature of flares and other high energy transient events. Flares are recognized to be important not only from

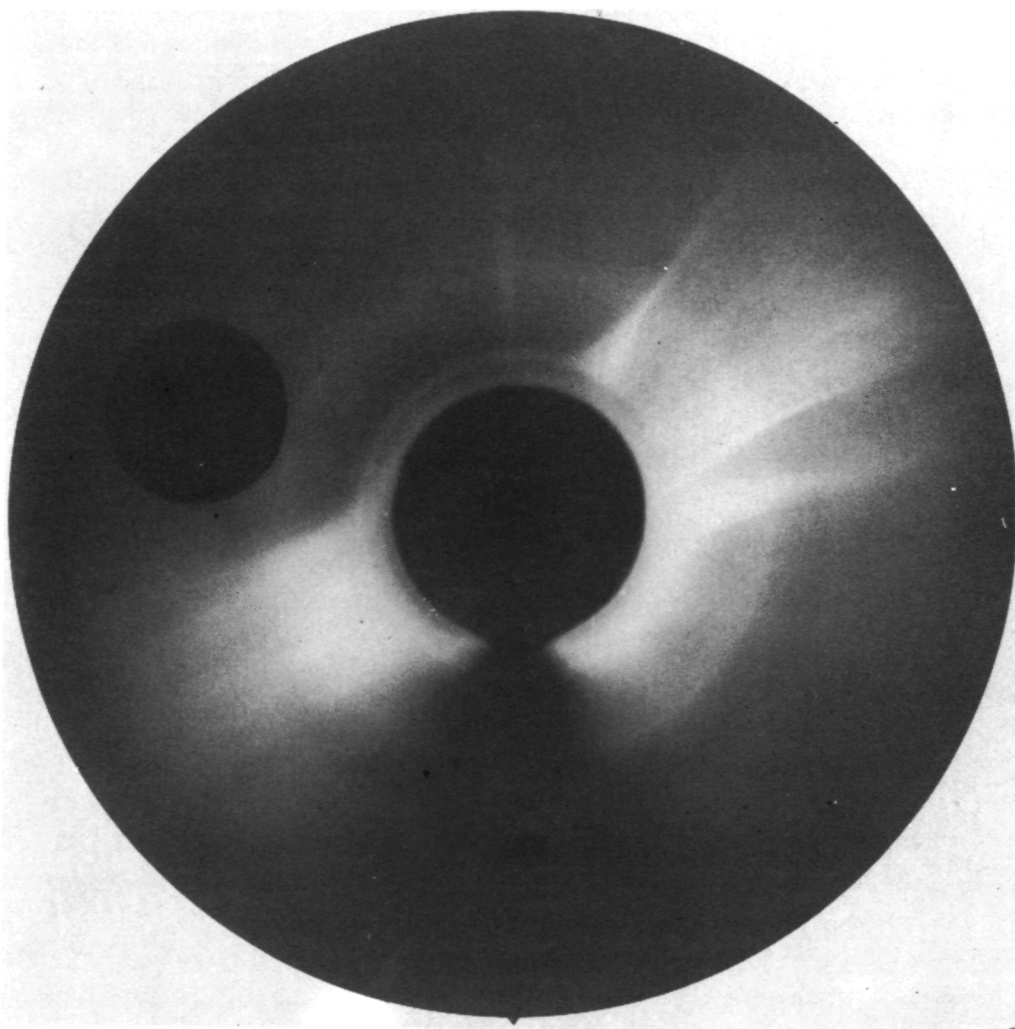


Figure 9. This photograph, made by ground command while the Skylab was over South America, shows the moon within the field of view of the coronagraph prior to the time of total solar eclipse as viewed by ground observers in Africa, in June, 1973. Picture courtesy of the High Altitude Observatory, Boulder, Colorado.

their inherent relevance to high energy astrophysics and to the physics of plasmas but also because of the many terrestrial effects that they induce. Processes known to occur in these events include energy storage, instantaneous energy release, the acceleration of particles to relativistic energies, explosive heating and evaporation, mass ejection and shock wave formation and the production of ultrahot (50 million degree) plasmas.

A general picture of a flare has been developed on the basis of past ground based and space borne observations of the different types of flare emission (Figure 10). The physical mechanisms actually responsible for the different phases of the event remain, however, a matter of considerable debate at this time.

It has been assumed for many years that a flare must derive its energy from the annihilation of magnetic fields and mechanisms have finally been proposed theoretically which can produce the necessary quantity of energy in a sufficiently short time. No observations to support this assumption have, however, been made nor has any clear evidence yet been found of the onset of an instability in any magnetic structure which has subsequently flared. Clearly, observations of a gradual energy build-up in a region prior to a flare and the determination of the physical location of the sudden energy release would contribute significantly to our understanding of this problem.

Past studies have revealed that the flare is a highly complex process. Hard X-ray burst observations and complementary ground based measurements of Type III radio bursts reveal the presence of subrelativistic and relativistic particles. The discovery of gamma ray line emission from the OSO-7 satellite showed that nuclear reactions occur in the more energetic events. The fine structure in the time histories of hard X-ray and radio bursts hint at a succession of acceleration processes and two or more stages are now proposed to account for the very high particle energies measured. Such processes have application in the theory of Seyfert galaxies and a variety of other astrophysical phenomena. Temporally and spatially correlated observations are now required to determine where these accelerations occur in the active region, what mechanisms are involved, and whether these highly energetic particles are solely responsible for all subsequent phases in the flare event.

It is known that during a flare the local plasma is heated to very high temperatures and it is assumed that the energetic particles are responsible. Correlated observations of the location of these particle beams with respect to the heated plasma, and of mass motions within the plasma, are still required in order that the validity of this theory may be demonstrated. The mechanisms whereby the heated plasma subsequently cools are also of considerable interest and their determination requires time correlated studies of the plasma temperature, geometry and motions during the cooling phase.

Finally, the mass ejection and shock wave formation processes which result in the type II and IV radio bursts, the coronal transients and solar wind disturbances are poorly understood. It remains a mystery why some flares produce measurable streams of particles at the earth while others, in equally favorable locations on the solar disc, do not. Equally mysterious is the peculiar elemental and isotopic composition of some of these particle events. Correlations of the properties of the accelerated particle beams at the solar surface with the properties of the associated coronal disturbances and with the measured properties of associated particle streams near the earth will help to clarify these questions.

Flares are not the only form of transient event whose effect is felt in the solar wind and at the earth. The ATM mission revealed that eruptive prominences are a common source of solar wind disturbance (Figure 11).

# PROGRESS TOWARDS UNDERSTANDING FLARES

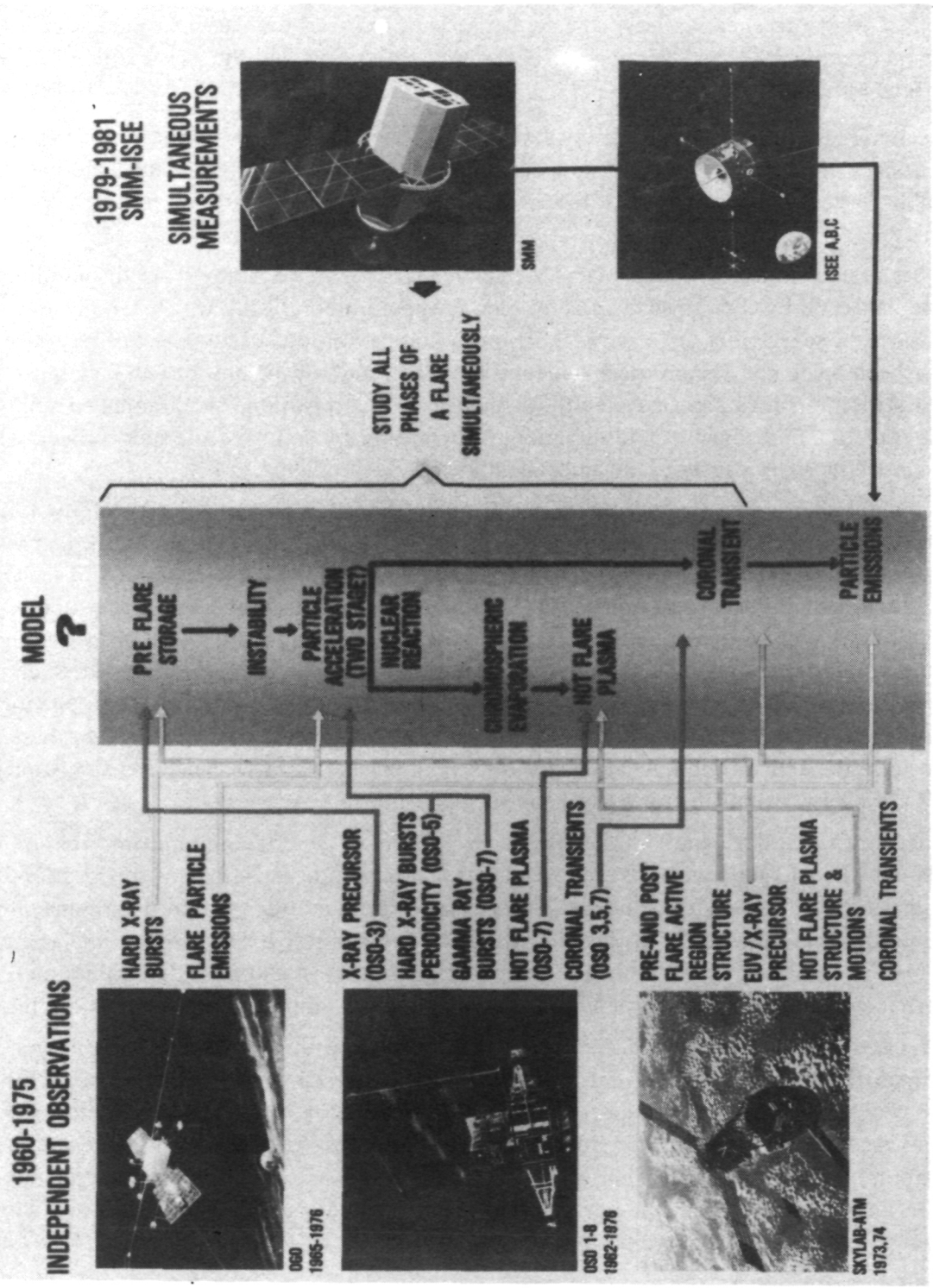


Figure 10

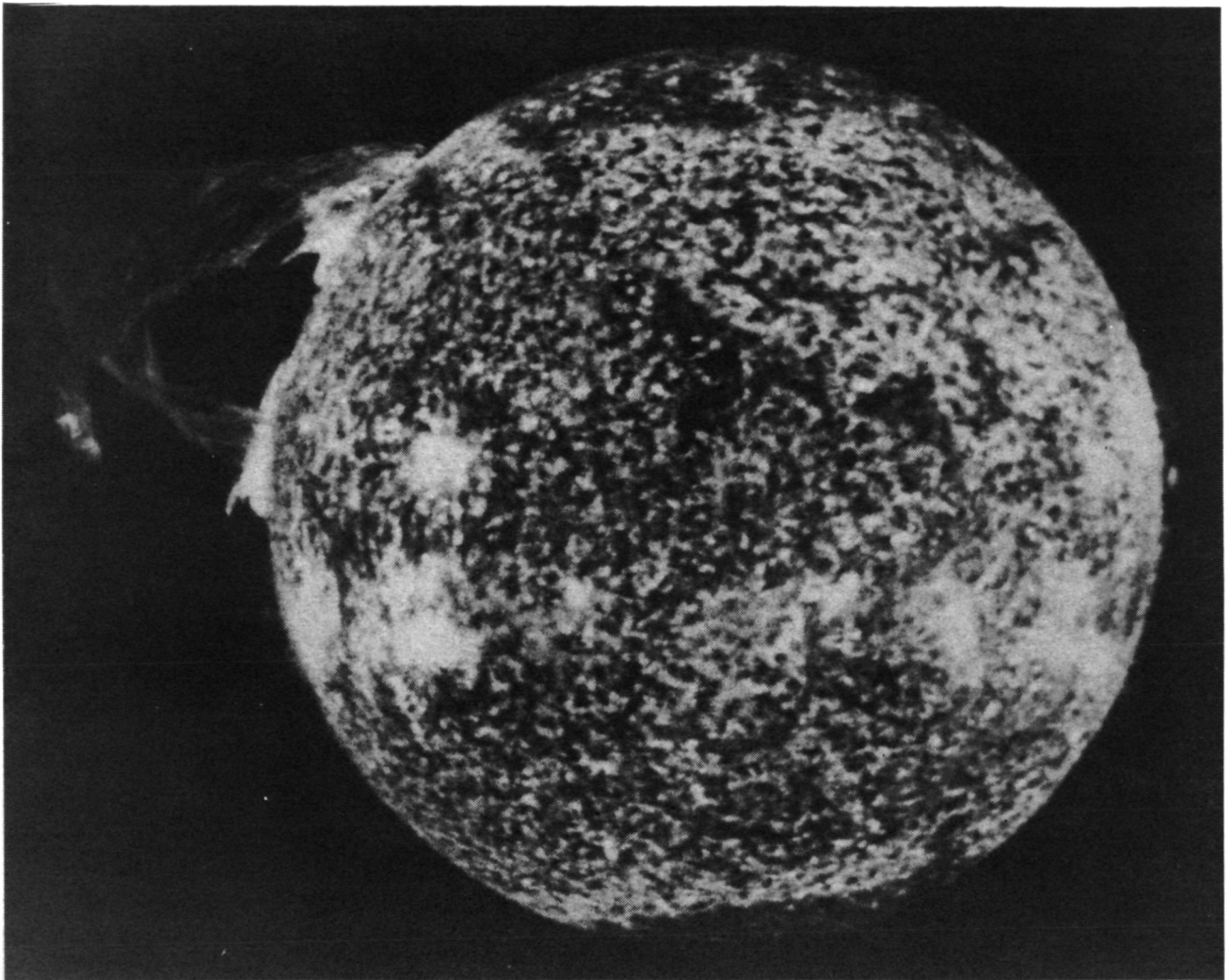


Figure 11. Photograph of the sun by the U.S. Naval Research Laboratory instrument on ATM, shows one of the most spectacular eruptive prominences ever recorded. The event spans over a half million kilometers on the solar surface.

Prominences, which are condensations of cool material formed along the neutral line in an active region magnetic field, present some serious physical problems in their own right. Foremost is the question of their energy balance and mass balance, although it is assumed that the insulating and supporting effects of the associated magnetic fields must play a dominant role in both aspects. It is uncertain whether material is continually transported in and out of these features or whether the original prominence material is derived from the corona or from lower levels. Indeed it is still uncertain as to whether a prominence is "solid" or consists of a collection of extremely thin magnetic flux strands although these extreme views result in radically different theories. High resolution observations of the structure and physical composition of prominences and of their associated fields are urgently required to resolve the problem.

Once a steady prominence can be explained the question of instabilities can be addressed, since it is instabilities which cause the eruption of these features and the subsequent coronal transient. Some excellent observations of the time history of prominence eruptions and of the associated coronal reaction have already been obtained by ATM and should contribute significantly to the solution of this problem.

### Future Flight Programs

*Solar Maximum Mission*—It is the opinion of the Solar Physics Community that the time is now ripe for an intensive, integrated attack on the flare problem. Considerable progress has already been made in understanding these events as a result of earlier ATM, OSO and OGO missions and a variety of models now exist to explain the various manifestations of the flare that are observed (Figure 12).

Since the onset of a flare occurs so rapidly this phase of the event is one of the greatest areas of uncertainty. It is known that a buildup of energy must occur prior to the event, and it is generally agreed that the only area in which this energy can be stored is in the active region magnetic field. Some form of instability is then assumed to occur and the magnetic energy is assumed to be suddenly converted somehow into highly accelerated particles. Evidence of preflare brightenings in extreme ultraviolet and X-ray wavelengths is sometimes seen preceding a flare and these would indicate that the energy storage might take place over a period of minutes to hours. It is, however, entirely possible that the flare is completely independent of these brightenings. Thus the time scale of the energy storage must still be regarded as an unknown quantity.

So far, the hard X-ray and radio burst data, from which the properties of the accelerated particles are derived, have had rather poor spatial resolution. It is therefore not known, at this time, where in an active region the flare energy is released, or, indeed, how it is released. Some scientists support the notion that the flare is triggered high in the corona and that the accelerated particles stream down the field lines, heating the lower, denser, layers and producing the nuclear reactions which give rise to the gamma rays. The hot flare plasma is also produced by this process. Other scientists favor a lower triggering point. No experimental evidence yet exists to support either concept. The only concrete fact is that wherever the energy storage and release occurs, it is of such a form that the underlying photospheric magnetic field configuration is barely affected.

Temporal variations in the hard X-ray and Type III radio burst emissions, together with measured variations in the steepness of the X-ray spectrum as a function of time, lead to the conclusion that the particle acceleration is at least a two stage process. The first stage is a highly efficient acceleration of electrons (and possibly protons) to energies of the order of 100 keV. This is followed by a possibly stochastic process (shock front associated) which increases the energies of the particles from 100 keV to over 10 MeV. This latter process may also be involved in galactic cosmic ray acceleration.

Popular theory then suggests that the accelerated beam impinges on the chromosphere causing material to be ejected into the corona with the formation of an accompanying shock wave and Type II and Type IV radio emissions. Other material splashes back up along the undistorted field lines and is the source of most of the thermal extreme ultraviolet and X-ray emission from the event. ATM observations confirm the existence of considerable amounts of turbulent motion and directed motion in the flare plasma, particularly in the chromosphere and low transition region. However, these data also



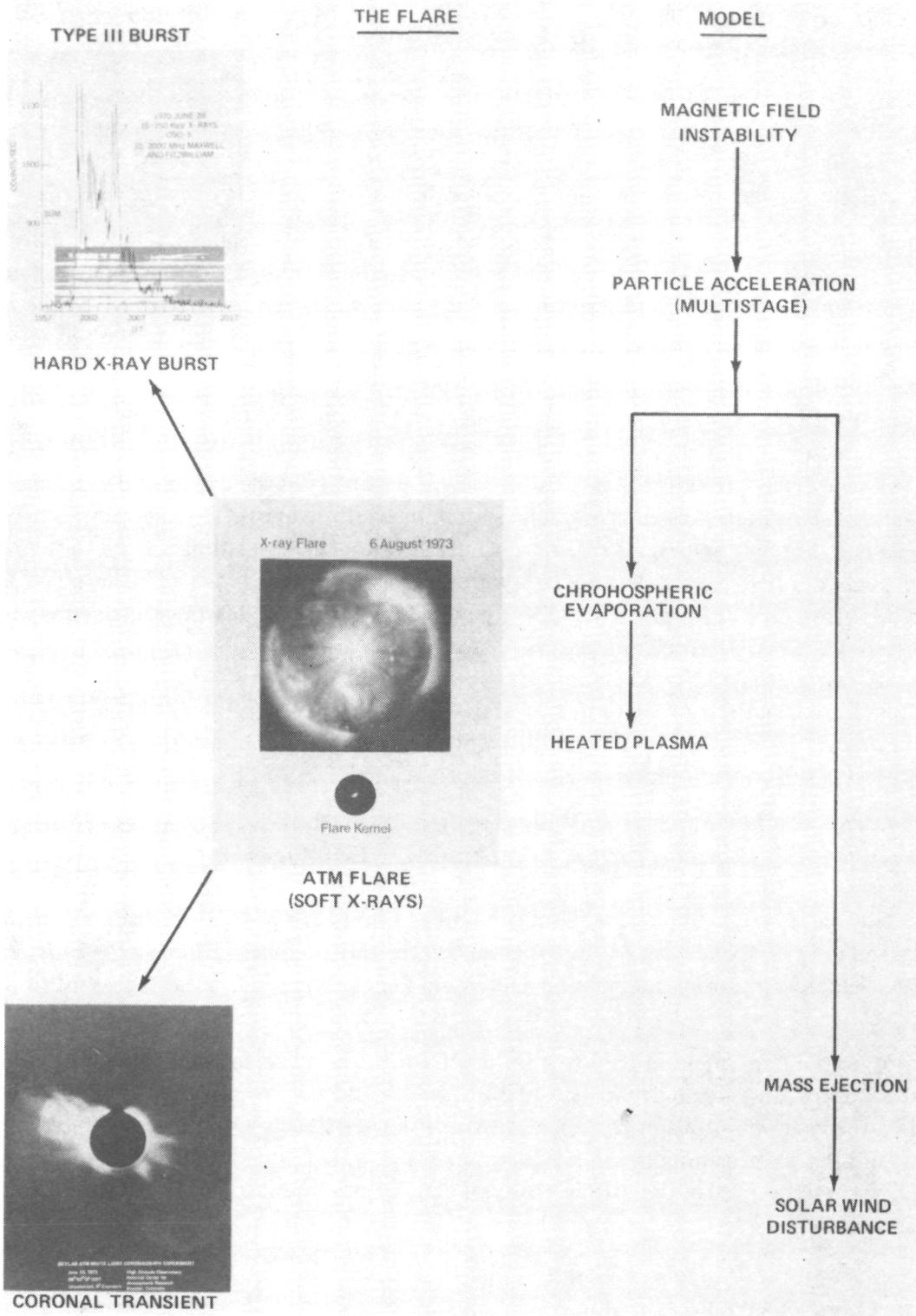


Figure 12. The flare model.

reveal that the hottest portion of the flare plasma lies at the apex of the active region loops, not at the foot points where the impact point is assumed to be.

Repetitions of the second stage acceleration process are assumed to occur as the shock wave passes through the corona. Since the volume in which these accelerations occur is presumably larger than that in which the primary particle beam is accelerated, this coronal phase of the flare may provide a convenient means whereby the secondary acceleration mechanism may be studied.

Indirect measurements of the properties of the accelerated particle beams may be made by observing the radio, hard X-ray and gamma ray emissions. In situ measurements of the elemental and isotopic composition of the ejected particles and of their energy spectra may, however, also be made and these provide additional information on the property of the flare region and on the acceleration mechanisms which occur.

The problem with all the past flare studies is that each has concentrated typically on a single aspect of the event and the spatial and temporal relationships between the various phases are, in the main, poorly known. There are thus some considerable uncertainties in the explanations given above. The Solar Maximum Mission represents a conscious attempt to eliminate these uncertainties by providing all relevant space borne observations of a flare, from the initial energy storage phase to the plasma cooling and coronal transient stages. The necessary ground based observations will be arranged as part of the SMM Guest Investigator Program. The SMM payload comprises hard X-ray and gamma ray spectrometers to study the particle accelerations and a hard X-ray telescope to determine their physical locations. Soft X-ray, extreme ultraviolet and ultraviolet instruments are used to study active region structure before, during and after the event, to search for evidence of energy buildup and to study plasma heating and cooling mechanisms. Finally, a white light coronagraph will provide data on the passage of shock waves through the corona and of the mass and energy of the material ejected.

Unlike its predecessors, the OSO's SMM is configured to enable all these measurements to be made simultaneously. It is also compatible with the Shuttle so that it may be retrieved after a suitable period of time and be refurbished and relaunched by Shuttle for other solar studies. The fall of 1979 has been selected for launch so that the mission will correspond to the projected period of maximum activity in the solar cycle. A one year slip in the launch date will significantly reduce the number of events likely to be observed during the mission and would hence severely degrade the scientific value of SMM.

In addition to the flare oriented payload, SMM will carry a small solar monitoring package designed to measure the strength and variability of the solar ultraviolet and visible light flux. The purpose of this addition is to enable variations in the solar constant to be studied as a function of time in the solar cycle in addition to measuring the shorter term increases in the uv, euv and soft X-ray regions which result from activity. These data should assist the many studies on solar terrestrial interaction which are currently underway.

*International Sun-Earth Explorer Missions*—The 1979 launch date of the Solar Maximum Mission is optimum from two viewpoints. Not only does it maximize the probability of observing a reasonable number of flares, but it also provides an opportunity for collaboration between SMM and the three members of the International Sun-Earth Explorer Missions, ISSE-A, ISEE-B and ISEE-C.

ISEE-A and B, the joint NASA/ESA "mother and daughter" satellites, are scheduled to be launched in the latter half of 1977 into highly elliptical orbits. There they will make simultaneous coordinated measurements of the solar wind and the magnetospheric composition and structure to investigate the interaction between the wind and the earth's magnetosphere. The third member of the trio, ISEE-C, will be launched in late 1978 into a heliocentric orbit and will be stationed near the sun-earth libration point on the sun-earth line, approximately 235 earth radii from the earth. It will be kept in place by means of a propulsion unit and will continuously monitor changes in the near-earth interplanetary medium.

Instruments carried on these satellites include plasma probes, low, medium and high energy proton and electron detectors, magnetometers, plasma wave receivers, cosmic ray detectors, electric field detectors, ion spectrometers and solar wind measuring devices.

The ability to compare the properties of the flare-induced particle streams at 1 AU with measured properties of the sun will finally remove some of the uncertainties that are inherent in the interpretation of in-situ particle measurements. Particle spectra and composition observed near the earth are influenced by propagation effects such as confinement and escape from the sun and by interactions with interplanetary magnetic fields. The collaborative studies will help to remove some of these uncertainties. The measurements of the ion and elemental abundances in particle streams will, in addition, provide valuable insight into the high energy processes occurring at the site of the flare. The charge states of the nuclear species accelerated in the flare, and measured by the ISEE experiments, can provide information on the temperature and composition of the acceleration region. These parameters may then be compared with similar information deduced from the SMM gamma ray observations. The conditions resulting in the anomalously high ratio of  $\text{He}^3/\text{He}^4$ , which is observed to occur for quite a number of flares, may also be explored since it cannot be explained on the basis of any existing theory. Finally, at periods of relatively low activity, the interface between the "quiet" solar wind and solar surface features can be explored.

#### Advanced Mission Concepts

*Shuttle Solar Physics Payloads*—The SMM is an example of a payload which has been optimized for a particular investigation. The emphasis on temporal and spatial correlations of the different manifestations of the flare, and the use of a free flying satellite to provide adequate statistics, are necessary requirements without which the objectives of the mission could not be fulfilled (Figure 13).

The requirement for spatially and temporally coordinated observations over a broad temperature (and hence wavelength) range is a common one in solar physics since the temperature of the outer solar atmosphere increases so rapidly as a function of height. While groups of instruments are invariably required to address even the simplest of solar problems, the composition of the group can change significantly from topic to topic. A study of the source of the solar wind structure might demand a payload comprising a medium resolution extreme ultraviolet telescope, a soft X-ray instrument, and white light and Lyman alpha coronagraphs. This would enable the temperature, density and velocity structure of the outer solar atmosphere to be determined and compared with corresponding in-situ measurement of the solar wind parameters. A second typical solar research project might be the determination of the role played by spicules in the coronal heating process. This might require a pay-



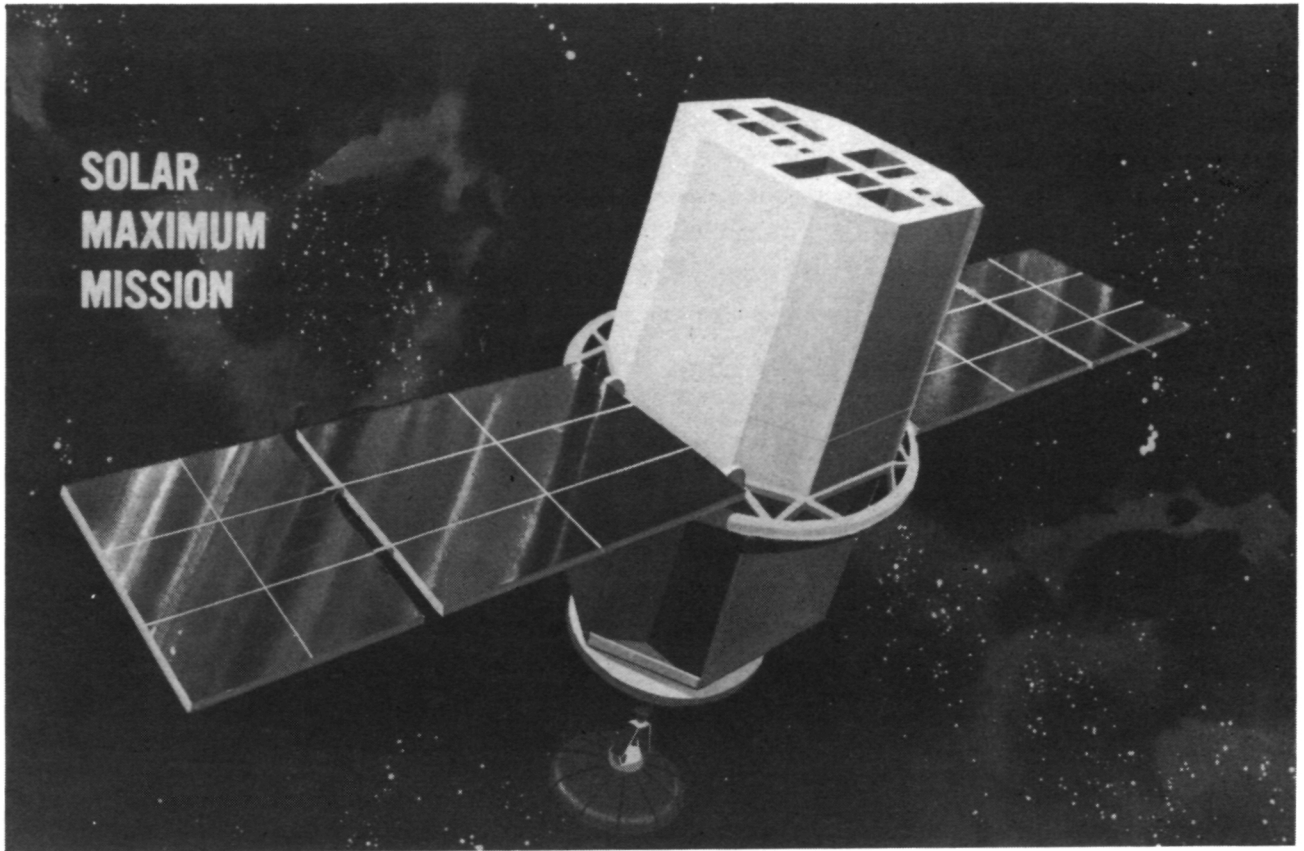


Figure 13.

load comprising a high resolution ultraviolet spectrometer, a sub-arc second resolution visible light telescope and magnetograph, and a high resolution extreme ultraviolet telescope. The entire spicule could thus be studied and its interface with the upper atmosphere determined.

Clearly, it would be impossible to configure a payload which is optimized to address all the important solar problems. It would similarly be impracticable to constantly assemble new, small, free flying missions, each optimized to address a new solar problem. Some alternate solution must therefore be found.

Spacelab potentially offers a solution to the dilemma. By making use of the existing solar instruments (ATM and OSO flight spare units, sounding rocket payloads, and SMM engineering models) and by extending the solar measurement capabilities by the gradual development of higher resolution "facility class" telescopes, it will be possible to assemble an inventory of instruments which is capable of tackling any problem. Subsets of the instruments can be selected according to the requirements of a particular investigation and can be integrated into the Spacelab and flown in a relatively short time and at relatively low cost. The retrievability of the Shuttle/Spacelab payloads enables individual instruments to be used a number of times in different studies. Methods of attack can be rethought and instrument complements reconfigured in response to new discoveries.

In order to be ready for the Spacelab, four teams of solar physicists have been formed to study the new flight opportunity and to define the new high resolution telescopes that will be required. Foremost among these is a one to one and a quarter meter aperture visible and ultraviolet light telescope which will have a variety of different focal plane instruments (spectrometers, magnetographs, etc.). This instrument will be primarily designed for studies of the photosphere and chromosphere and will have a fraction of an arc second (70-140 km on the solar surface) spatial resolution. Such an instrument will be able to conduct the temporal studies of fine scale features which are impossible from the ground due to seeing limitations, and will thus be invaluable in such areas as the investigation of condensed magnetic flux tubes, or the role of spicules in coronal heating.

Equally valuable will be a grazing incidence extreme ultraviolet telescope covering the range from about 50 Å to 500 Å with high spectral and high spatial resolution. This will enable corresponding studies to be made of the chromospheric network, active regions, prominences, and, with luck, the occasional flare, in the region between the lower transition region and the lower corona. A hard X-ray telescope with a spatial resolution capability of about 4 arc seconds is also considered to be desirable in the early Shuttle era to complement the SMM mission. The last two facility class instruments, the soft X-ray telescope (2-50 Å) and the extreme ultraviolet telescope (300-1200 Å), will be developed last, after the full potential of their lower resolution ATM counterparts has been realized.

While three of the four teams devote their time to the definition of facility class instruments, the fourth is considering the more general problems of Shuttle operations. The interests of this team range from the production of an inventory of available instruments, and the identification of the changes necessary to render them Shuttle compatible, to the determination of telemetry and data storage requirements and the investigation of appropriate pointing systems. Considerable effort is being expended in this latter area so that suitable pointing and rastering systems will be available for all classes of solar instruments.

*Out of Ecliptic Mission*—The discovery of a definite link between some form of solar output and the terrestrial climate has stimulated an intensive research effort to try to determine the mechanisms causing this effect. One of the prime suspects is the solar wind and cosmic ray flux. While the ISEE/SMM combination should help throw some light on this problem, it will be unable to answer one fundamental question—how would the structure of the solar wind change if the sun were to suddenly revert into its low activity “Maunder minimum” mode?

A new approach to this problem may be possible if the wind structure and composition is sampled at high solar latitudes where coronal holes appear to be the dominant solar features. In view of the relationship between the recurrent high velocity streams and coronal holes, it is reasonable to assume that the wind at these latitudes will have properties quite different from those generally measured in the plane of the ecliptic and in the active longitudes ( $\pm 40$  degrees). If the 70 year Maunder minimum resulted effectively in a hole existing over the entire solar surface, then the measurement of these polar winds may provide data on the condition of the wind during this period.

The most cost effective means currently available for obtaining high latitude samples of solar wind composition and structure is to use a pair of Pioneer type spacecraft and to send them into a trajectory which swings by Jupiter and hence over the north and south poles of the sun. This concept is called the Dual Jupiter Swing By and is the subject of a joint NASA-ESA study at this time. Since

the Pioneer type of spacecraft are small and have no three axis stabilization, they cannot be used to carry any sophisticated solar imaging experiments. Reasonable complements of solar wind and cosmic ray measuring instruments can, however, be carried, and the missing observations of the solar surface structure can be obtained from another source. This other source is the Solar Maximum Mission spacecraft, which, after retrieval, refurbishment and some slight modification to the payload, will be able to obtain all the necessary observations of the solar coronal structure.

Later Out of Ecliptic Missions may make use of solar electric propulsion to carry a heavier and more sophisticated imaging payload to high solar latitudes. This option is also under study.

*Solar Stereoscopic Mission*—One of the major surprises in the ATM data was the extreme variability of virtually every type of solar feature. This finding was scientifically interesting but posed some unforeseen problems in interpretation since the techniques developed for deconvolving selected features, by using time series of images, could no longer be applied. The other means whereby accurate three-dimensional structural information may be obtained is by making simultaneous stereoscopic sightings and it is on this principle that the Solar Stereoscopic mission is based.

The proposed mission once more capitalizes on the fact that the refurbished Solar Maximum Mission, with its Out of Ecliptic Mission payload, is also an ideal mission to complement the Solar Stereoscopic Mission (SSM). By flying a similar, or slightly less sophisticated solar imaging payload on SMM, together with a solar particle and wind monitoring package, and by placing the satellite at the appropriate distance eastwards round the ecliptic, the SSM/SMM duo would have the capability of not only studying three dimensional structure and evolution of coronal streamers, active regions and coronal holes, but it could also study the properties of solar wind structures before they rotated round to the position of the earth. The eastward location of the SMM would also enable early warning to be obtained of active region development.

*Further Advanced Mission Concepts*—In addition to the missions just discussed, a variety of additional solar projects are currently being considered. These include a “solar probe” which would carry a complement of particle and wind monitoring experiments in towards the sun so that the variation of solar wind properties within the first 50-100 solar radii of the sun could finally be measured.

The sun is coupled to the terrestrial environment through the photons, particles and magnetic fields it emits. It is only natural that a program to study the forces that shape and control the magnetosphere and ionosphere goes hand in hand with a program in solar physics.

## STATUS OF MAGNETOSPHERIC PHYSICS

### Introduction

Although we expect that there will be some refinements, and perhaps even some surprises, we believe we now have a fairly good description of the immediate space environment of the earth. This has come after a period of exploration, a period of data-gathering, and a painstaking analysis of the information returned from our scientific instruments in space. In less than 20 years after the launch of the first Sputnik, we have a better description of our spatial environment than Christopher Columbus had available of the surface of the earth from all of man's previous recorded history. So what is there still to do? For us, the description is but a prologue—the task is now to understand the titanic forces

of nature which shape this environment, and which control the very conditions which make life possible here on earth. The desire to understand the interplay of forces which produce our environment is, in itself, a worthy intellectual endeavor for homo sapiens, but it has recently acquired more urgent overtones with the realization that man now has the power to cause irretrievable damage to his surroundings which could endanger his very survival. We need to know how nature works in order to avoid such a threat, and to look for ways to apply this knowledge for the positive benefit of mankind.

The sun is by far the most important source of the energies which surround us and which are of prime importance in shaping our environment. But the visible light, which is needed for plants to grow and which drives the weather systems in the lower atmosphere, represents only a part of the emission from our nearest star. There are two other major flows of energy: the solar wind, and the short wavelength radiations in the ultraviolet and X-ray parts of the spectrum.

### The Magnetosphere

The solar wind consists of a stream of particles, mostly protons and electrons, traveling with speeds in the neighborhood of 300 km/sec (670,000 miles per hour), and dragging with them a weak magnetic field. This particle stream interacts with the outermost portions of the earth's magnetic field, and flows around it, like a stream of water around an obstacle, producing the magnetospheric envelope with a long comet-like tail, as shown in Fig. 14. Since the particles are charged, their impact with the earth's magnetic field produces an electric field, and a hot convecting stream of particles moving with speeds in excess of 100,000 miles per hour. The actual interactions are, in fact, very complicated, and

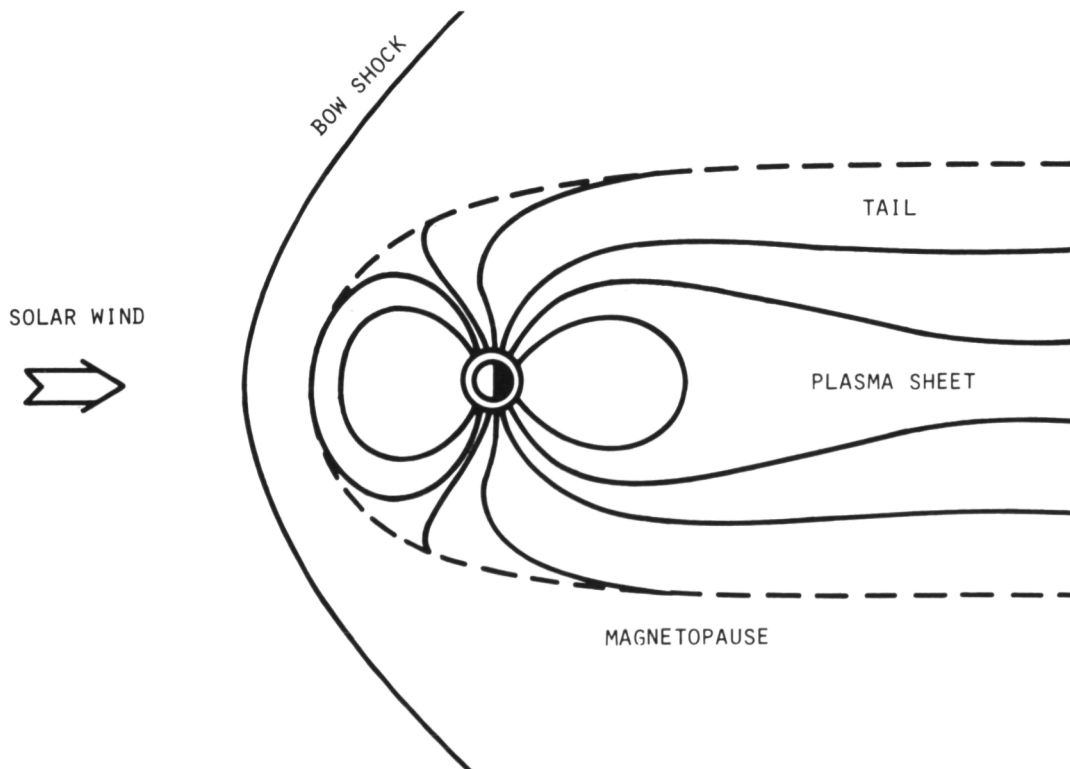


Figure 14. The shape of the earth's magnetosphere viewed from the plane of the ecliptic.

it will be the goal of the International Sun-Earth Explorers (ISEE-A, B, C) to study them in some detail. While ISEE-C observes the incoming solar wind, the twin spacecraft ISEE-A and ISEE-B will measure the response of the magnetosphere to the solar wind and the fluctuations in the solar wind.

The other inputs to the near-earth system, the ultraviolet and X-ray components, interact much lower in the atmosphere. With a quiescent sun, the ultraviolet interaction is most important, occurring at altitudes in the 100-300 km (65-200 miles) range. This interaction produces the ionosphere, which supports long-distance radio communications. The details of this interaction are being studied by the Atmosphere Explorers (AE-C, D, E). These interaction processes also result in a current system which, in turn, generates an electric field, but at much lower altitudes than that generated by the solar wind.

Between the outer parts of the magnetosphere, 80,000 km (50,000 miles) from the earth's surface, and the lower interaction level, there is a very complex region which is partly controlled from above, and partly from below. We are currently studying an Electrodynamic Explorer mission which will address itself to the manner in which the upper and lower levels are coupled, and in turn control the intervening space. This concept of coupling is one whose importance has only recently been understood. It means that the environment of the earth cannot be separated into independent portions and considered in isolation. Just as oxides of nitrogen and freon released at ground level can profoundly affect the ozone layer near 30 km (19 miles), so we have discovered that other large-scale processes result in one portion of the earth's environment affecting another.

The impact of the solar wind on the outer portion of the magnetosphere results in a "collisionless bow shock" at a distance of about 12 earth radii (50,000 miles) from the sunward side of the earth. The existence of such a shock in the tenuous plasma of the outer magnetosphere was an unexpected discovery made in about 1964. This discovery provided the impetus for an increased effort in the study of plasmas, which are gases made up mostly of charged particles. Most of the matter in the universe is in the plasma state.

In a much denser form than seen in the magnetosphere, plasmas are believed to hold the key to the generation of power by nuclear fusion. Although most of the solar wind is swept around the magnetosphere of the earth, a small fraction (about 1 percent) succeeds in entering the magnetosphere, where it is believed to produce the radiation belts. The method of entry is not yet understood, but one possible doorway is at the "neutral points" where the magnetic fields of the earth and solar wind approximately cancel each other. Conditions in the neighborhood of the neutral points have been studied by the HAWKEYE spacecraft, which is observing the magnetic fields, the plasma flow and the radio emissions from the magnetosphere.

The magnetosphere of the earth is a source of radio waves. Auroral activity generates intense bursts in the 100-500 KHz range. These frequencies are a little below the AM broadcast band. Similar radio emissions are also observed from Jupiter, and have been reported from Saturn. Continuing the combined efforts of HAWKEYE, the Interplanetary Monitoring Platforms (IMP) and Radio Astronomy Explorers (RAE), an additional, weaker component has been observed at lower frequencies. This radiation appears to originate inside the magnetosphere in a broad region between the plasmopause (which separates the lower, cool, co-rotating plasma from the upper, hot, convecting plasma) and the magnetosphere boundary. Understanding the origin of these radio emissions is important in interpreting the radio signals from distant parts of the Universe which are studied by radio astronomers.

As the solar wind sweeps past the earth, it intersects with the earth's magnetic field, causing massive electrical charge displacements (currents) from the dawn to the dusk side. These are indicated in Fig. 15. The situation is analogous to the current system in an electrical generator. From inside the magnetosphere, these displacements are seen as an electric field which, in turn, drives currents across the magnetotail (labeled "neutral sheet current" in Fig. 15). These currents squeeze the tail region into a thin plasma sheet. When there are solar storms which release abnormal amounts of plasma from the sun, the entire magnetosphere is compressed in size, and this compression induces a "ring current" of particles with circular paths in the lower magnetosphere. It has recently been discovered that atomic oxygen ions can, at times, be a significant portion of the ring current particles. These are almost certainly brought up from the lower portions of the earth's atmosphere or the ionosphere, since they are present in only minute amounts in the solar wind. How these particles get there, however, remains an

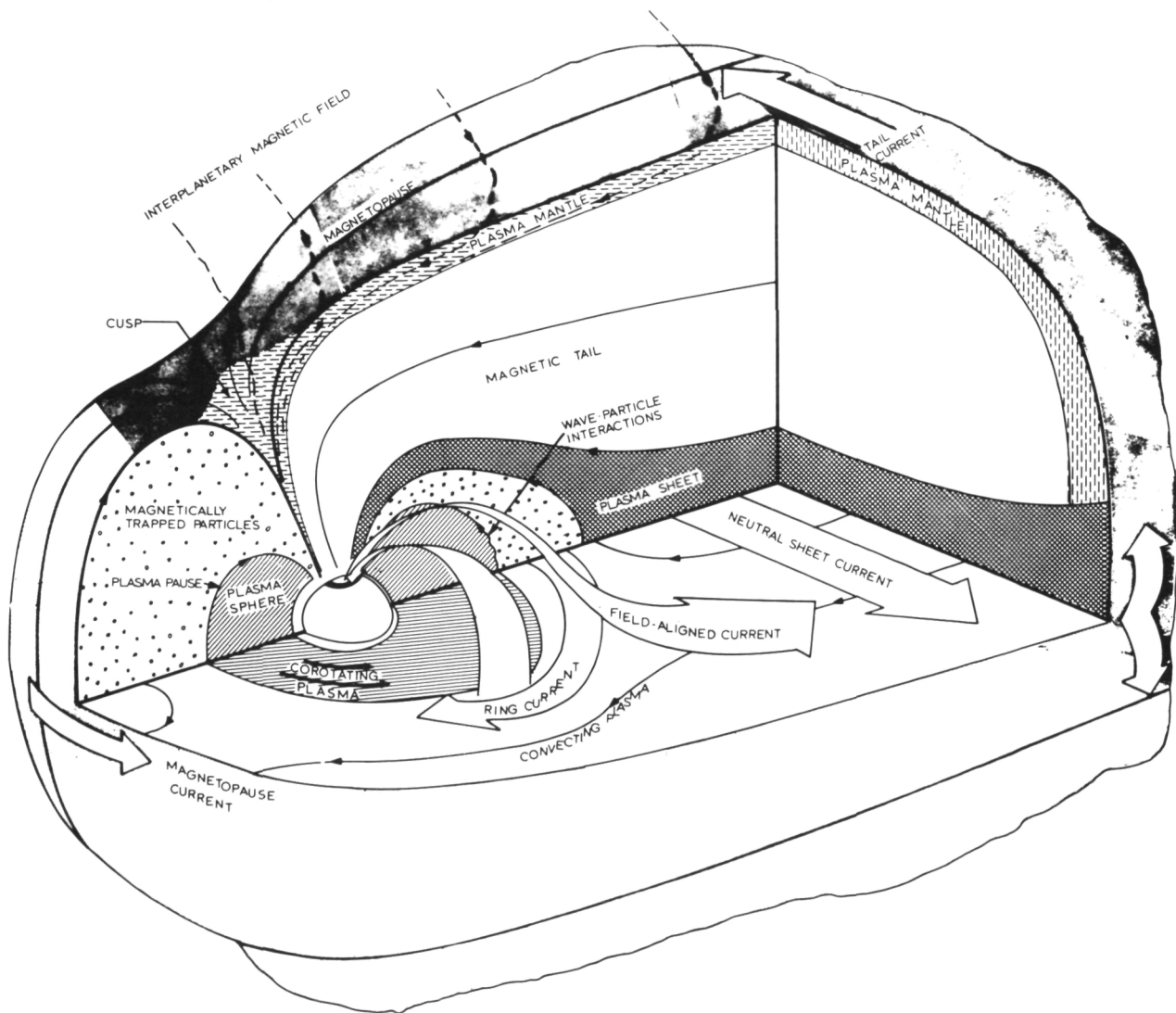


Figure 15. The earth's magnetosphere.



outstanding mystery. The analysis of the events which affect the ring current system is continuing with data obtained from Explorer 45 under the Data Analysis program.

In response to stimuli which we do not fully understand yet, but which may be related to changes in the interplanetary magnetic field, magnetospheric substorms occur. As shown in Fig. 16, the plasma sheet is compressed, a reconnection of magnetic field lines occurs as shown by an asterisk

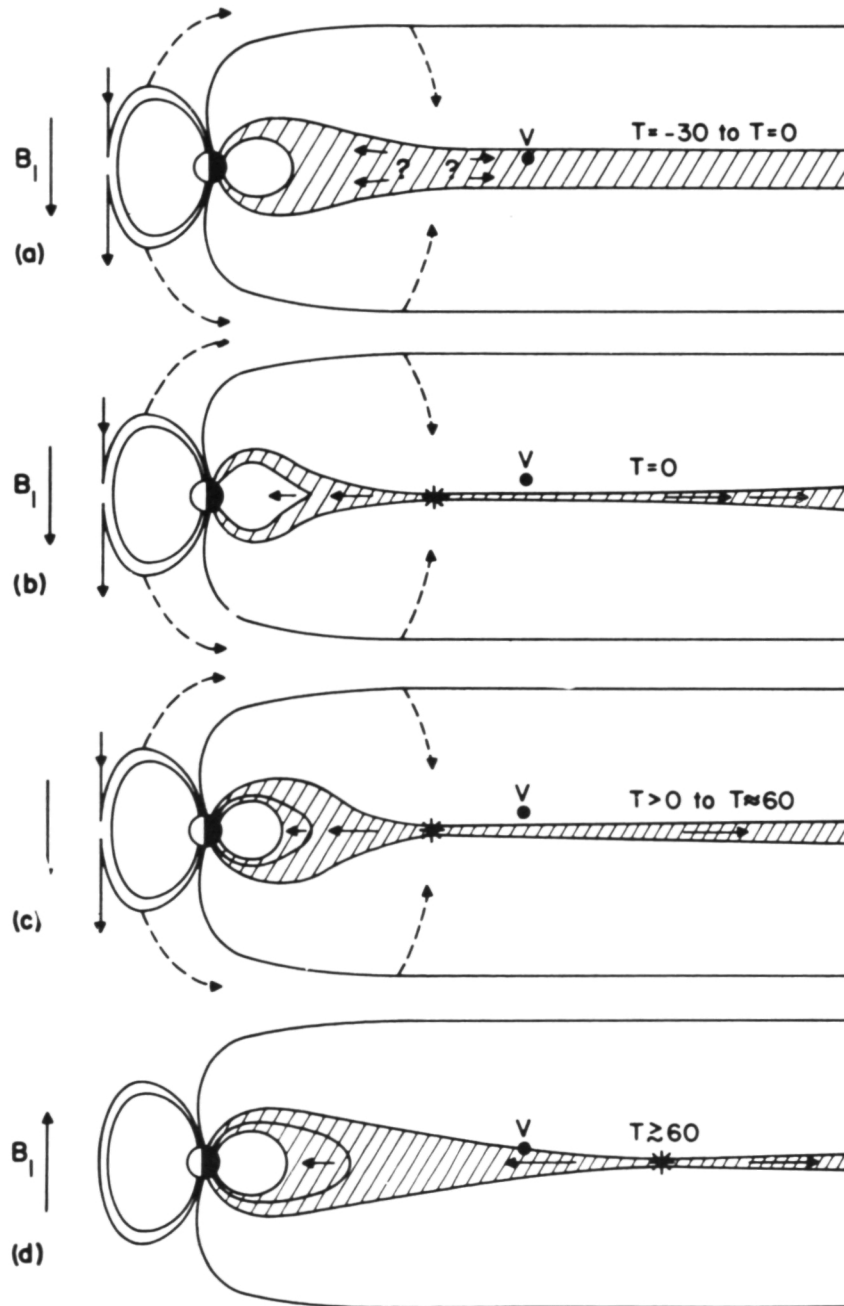


Figure 16. Model of the events leading to a magnetospheric substorm.

isk, and large amounts of energetic plasma are pushed towards the earth. Such large-scale plasma motions are often accompanied by brilliant auroral displays and fluctuations of the earth's magnetic field which produce some deviations of magnetic compass needles. Large storms have even resulted in disturbances on electrical power distribution systems. We would be of significant help to power company operations if we could understand better and even predict these events.

Figure 17 provides a closer look at the magnetosphere near the planet earth. This region is rich in a whole variety of phenomena. Near the poles is a region where atmospheric constituents are swept into space by the polar wind. The figure shows the boundaries of the radiation belts, the ring current

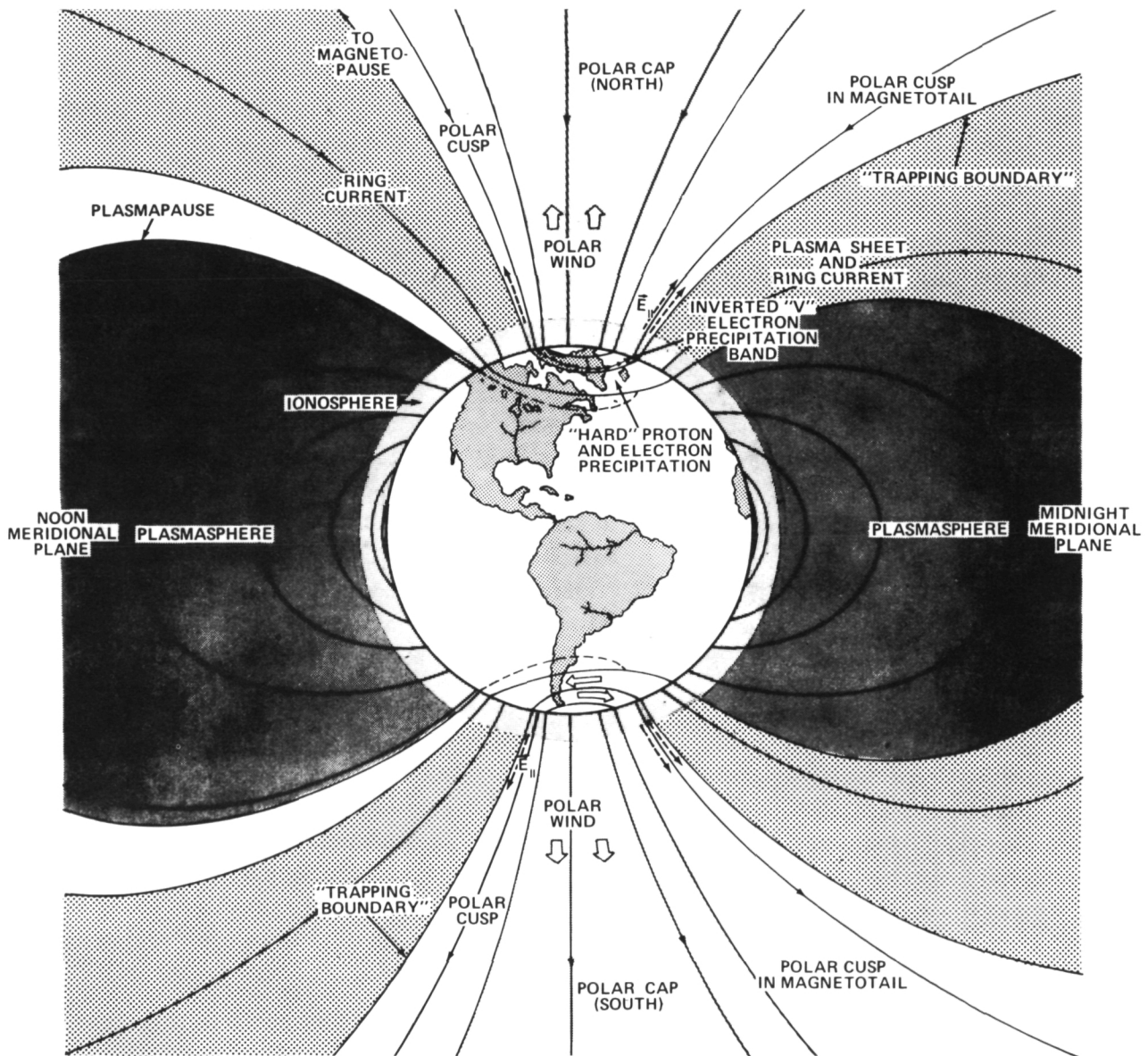


Figure 17. The magnetosphere near the earth.



regions, the plasmasphere, and the outer magnetosphere. This composite snapshot provides an average picture: at any one time, the magnetosphere presents a pulsating, dynamic response to the fluctuating stimuli received from the sun.

Because charged particles can travel freely down the lines of the earth's magnetic field, electric fields at high latitudes are carried down to ionospheric altitudes of 100-300 km (60-190 miles) where they drive current systems called auroral electrojets. This is an example of the outer, solar wind influence affecting the lower levels, which are otherwise controlled by solar ultraviolet radiation. Indeed, the Atmosphere Explorer (AE-C, D, E) satellites have shown that, on many occasions, the energy input from particles at high latitudes can exceed that due to the solar photons even at ionospheric levels. This is one mechanism whereby the upper magnetosphere is coupled to the ionosphere. The ionospheric currents, in turn, couple back to drive the magnetosphere. We hope to study this coupling more closely with the Electrodynamical Explorer (EE) program.

Figure 18 shows the results of a theoretical model of the electric fields which drive the magnetospheric plasma. The figure shows the electric potentials—the electric fields are perpendicular to the equipotential lines shown. On the left are the flow lines due to the external field. On the right, we have added the effect of the lower plasma and magnetic field sticking close to the earth, and co-rotating with it. This results in part of the magnetospheric plasma being trapped, with the formation of a bulge on the evening side. We believe that portions of this bulge can break off under disturbed conditions. Such models provide enough understanding of the complex interrelationships between the atmosphere, the ionosphere and the magnetosphere to define the measurements needed to understand the detailed processes which occur there.

As presently envisaged, we consider EE to consist of two spacecraft, one in a high, and the other in a low orbit. A significant number of measurements would be made at two places on the same magnetic line of force, so that we may study these currents and the acceleration of auroral particles. It is now known that the earth's magnetosphere can act as a large particle accelerator, and produce low energy cosmic rays. Similar events seem to take place in the magnetosphere of Jupiter, where cosmic ray particles of somewhat higher energies are produced and have been observed by Explorer 47 and Pioneer 10. A study of these acceleration mechanisms close to home may, therefore, shed light on the production of cosmic rays elsewhere in the universe. Figure 19 shows the two EE spacecraft with the data going to a central computer at the Goddard Space Flight Center and accessible via telephone line to the user community.

Both EE spacecraft will be placed in polar orbits, and have on-board propulsion systems. Both will carry particle and field instrumentation. In addition, the lower spacecraft will be able to measure the atmosphere and its motions, and the upper will be able to provide pictures of the auroral zone. A key element in the mission is the direct accessibility of all the data on-line to members of the Investigator team, who will then be able to program the spacecraft to optimize their operation based on a preliminary assessment of the results. This concept has been tested and shown to work well in the Atmosphere Explorer (AE) program.

The last two spacecraft in the AE series, AE-D and AE-E, were launched on 6 October and 19 November 1975, respectively. Their primary mission is to investigate the details of the sun-atmosphere interaction in the 130-320 km (80-200 miles) region. A Backscatter Ultraviolet Spectrometer (BUV)

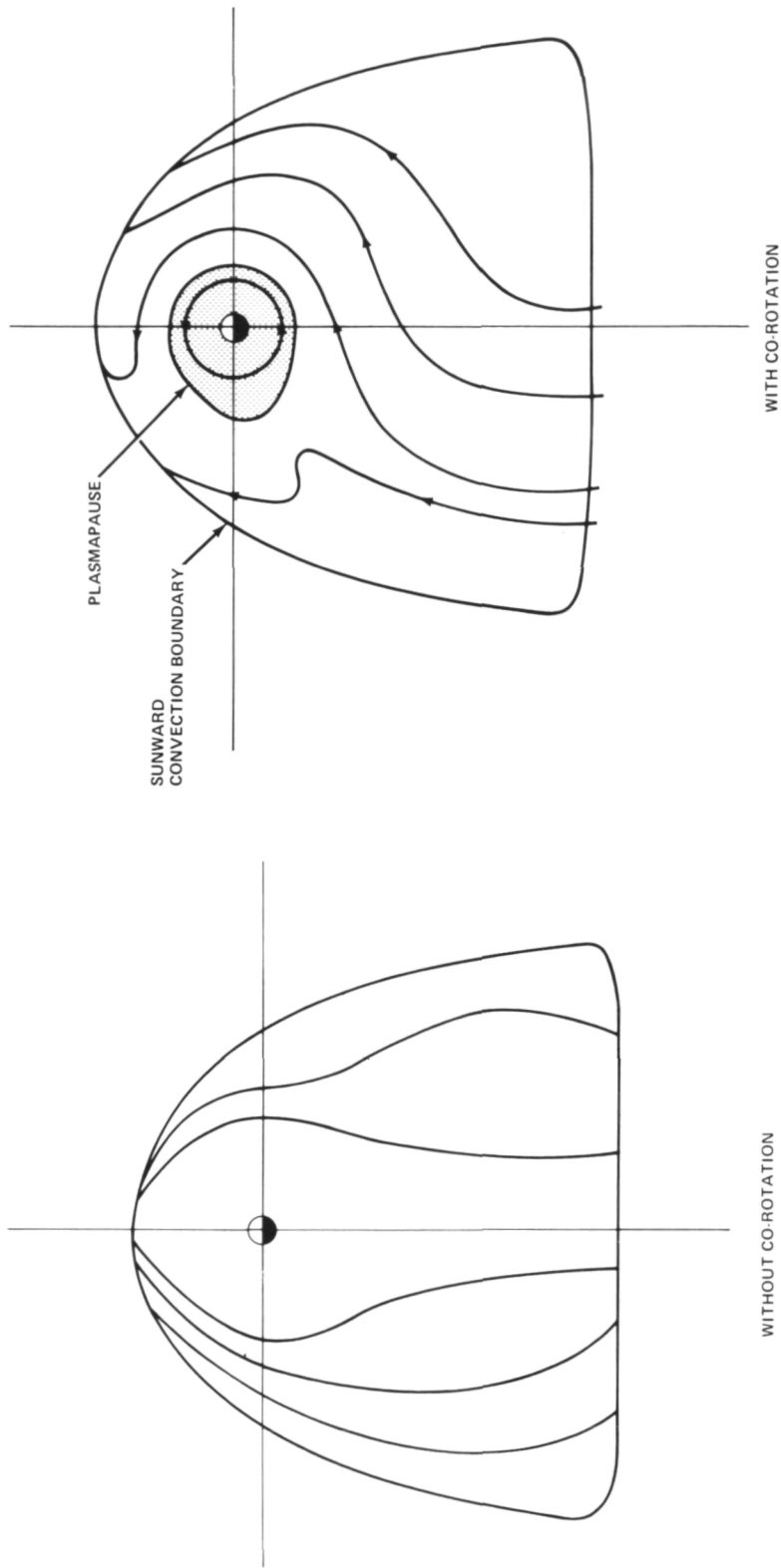


Figure 18. Electric fields in the magnetosphere, seen from above the north pole. Lines of constant electric potential are shown, for the case that plasma near the earth does not co-rotate with the earth and the case when it does co-rotate.

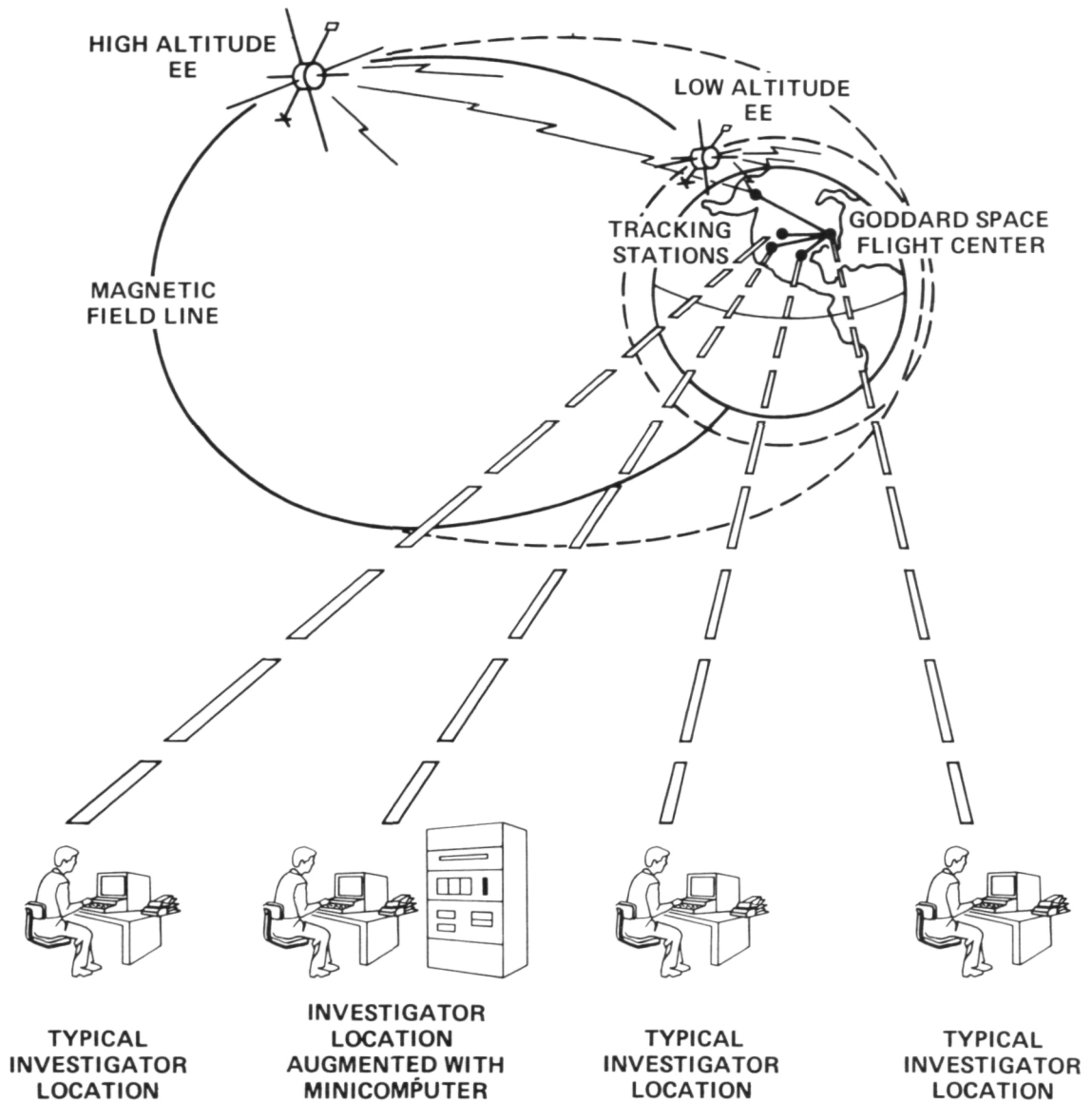


Figure 19. The Electrodynamic Explorer Project.

was added to AE-E to provide measurements of atmospheric ozone to complement the data available at other local times from other spacecraft, e.g. NIMBUS. Detailed maps of atmospheric ozone are a necessary step in determining the stability of the ozone layer to natural and man-made perturbations.

The results coming from AE indicate clearly the importance of large-scale motions, vertically and horizontally, of both neutral and ionized components, with wind speeds over 100 m/sec (200 miles per hour) quite common. The photoelectron spectrometer has shown the detailed electron spectra which result from the ionization of atmospheric constituents by the sun. Figure 20 shows a series of such spectra. The marked bump near 27 eV is due to the ionization of atomic oxygen by the solar helium line at 304 Å, an important reaction in the production of the ionosphere. The same instrument

PHOTO ELECTRONS

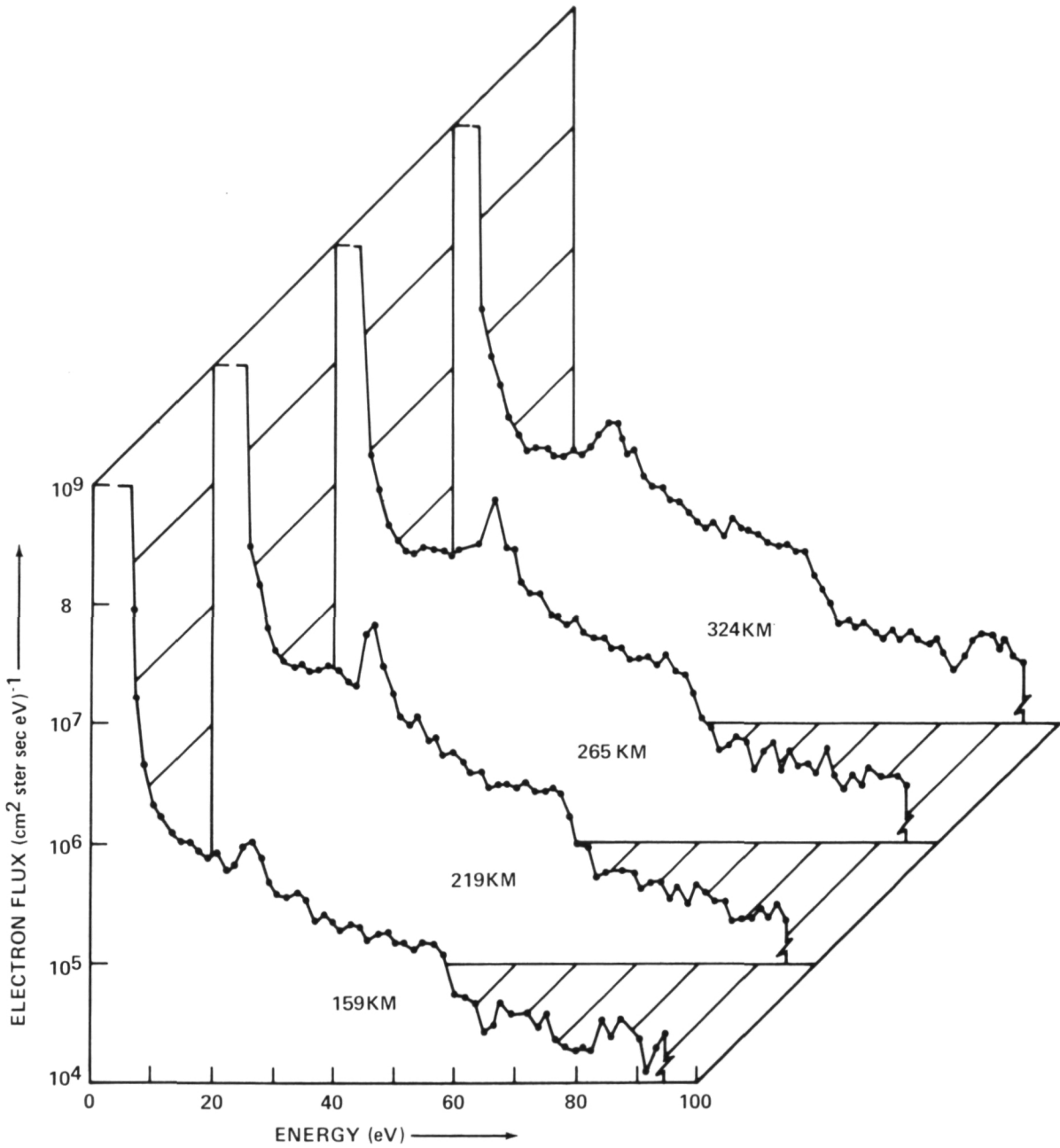


FIGURE 20  
Photoelectron Spectra from Atmosphere Explorer

shows several classes of events in the high latitude auroral regions, suggesting both a steady drizzle of incoming particles and successive pulses which appear to result from specific acceleration mechanisms. Figure 21 shows some of these high energy electrons at high latitudes.

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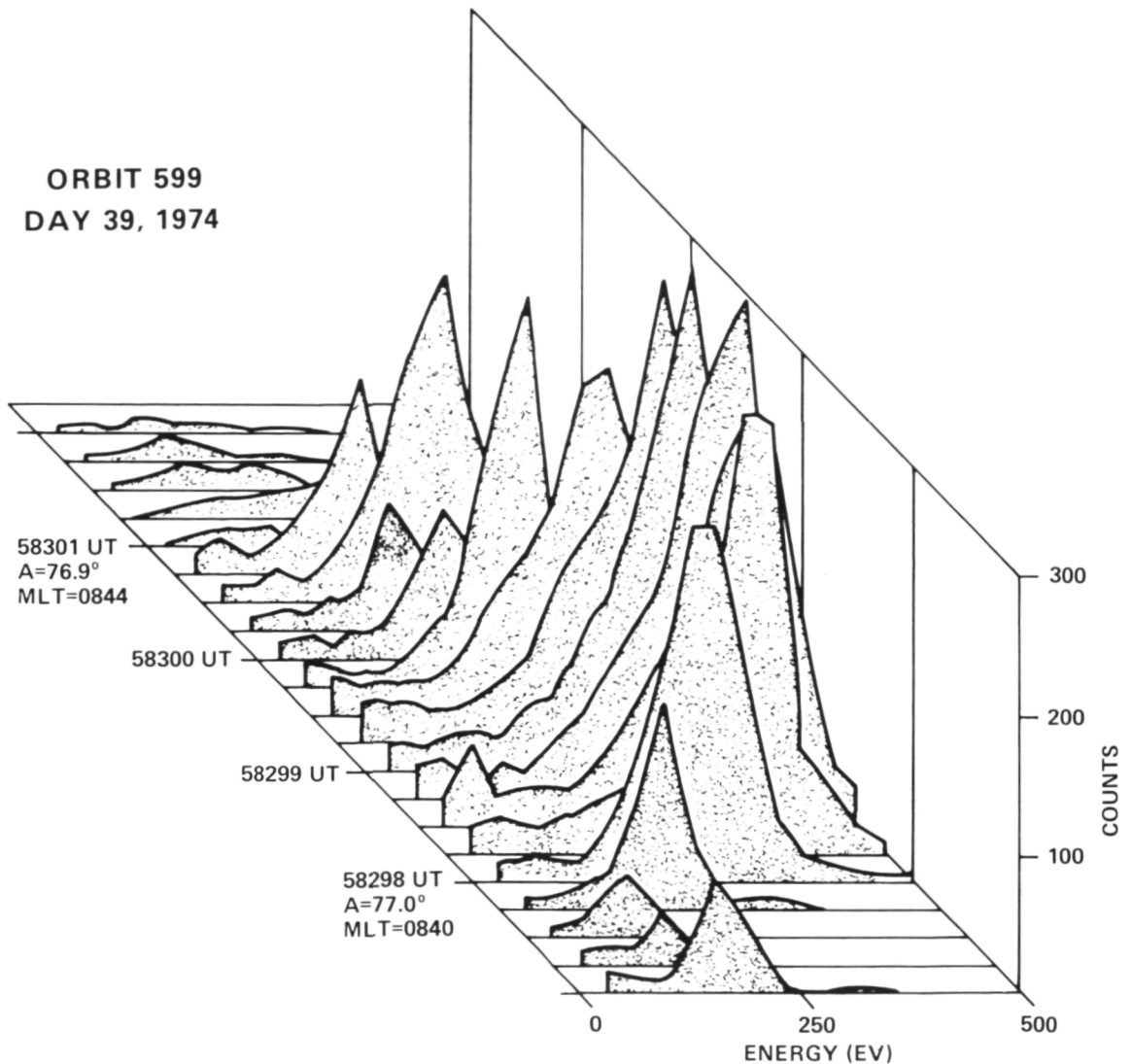


FIGURE 21

HIGH ENERGY ELECTRONS AT AURORAL LATITUDES (FROM AE)

Atmosphere Explorer-C has measured the variation of nitric oxide (NO) as a function of latitude at about 105 km (65 miles). Contrary to early expectations, NO increases at high latitudes, where it shows more day-to-day variability, strongly suggesting a particle origin. Typical data are shown in Figure 22. Although AE is studying a region well above the ozone layer, many of the reactions which control the ozone layer may also be studied, and their reaction rates measured. In particular, the important role played by atomic nitrogen is just being understood. Contrary to earlier ideas, atomic nitrogen is sufficiently abundant to affect the ionospheric composition, and produces nitrogen ions both by charge-exchange with ionized oxygen, and by direct photo-ionization. At night, it also pro-

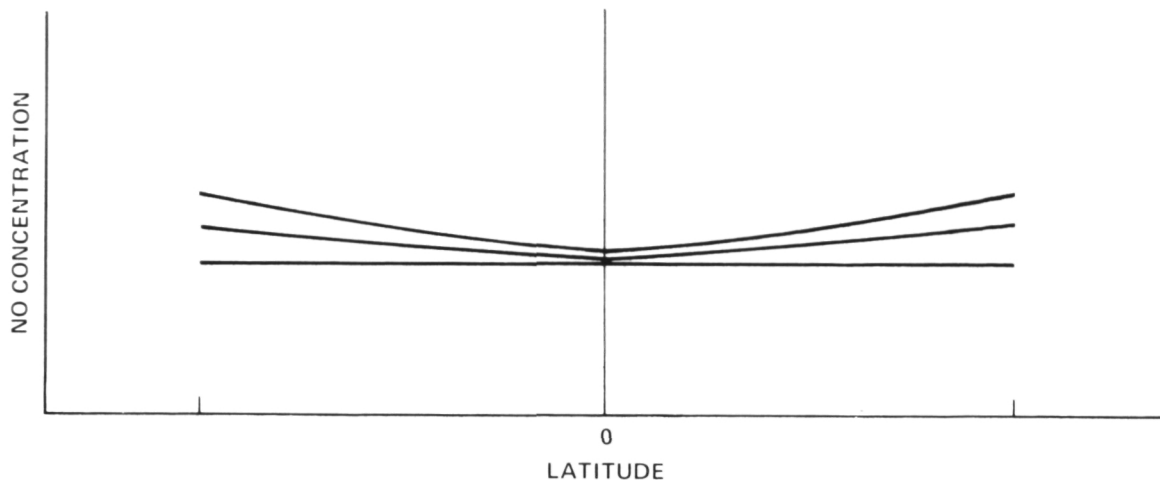


Figure 22. Nitric oxide variation with latitude. The tic marks indicate the earth's poles. Each curve represents a different day.

duces nitric oxide ions in a reaction with ionized molecular oxygen. In the chemistry of the atmosphere, the incorporation of atomic nitrogen thus provides a new source of  $\text{NO}^+$  and a new sink for  $\text{O}_2^+$ .

Electrodynamic Explorer (EE) will study the major questions of the interrelation between the atmosphere, magnetosphere and ionosphere. We are also studying a possible cooperative particle release experiment with Germany called AMPTE (Active Magnetospheric Particle Tracer Experiment). This mission will address the question of the flow of plasma and the entry of solar wind particles in the magnetosphere by releasing small quantities of trace constituents, such as lithium and strontium, and watching them enter into the magnetosphere. The Electrodynamic Explorer may be able to perform the diagnostic function without launching an additional spacecraft for this purpose. Another way the EE mission may be enhanced is by another Scout-launched Hawkeye to make complementary measurements from a different orbit.

In addition to the electric current systems so far mentioned, there is another important belt of electric current known as the equatorial electrojet which follows the magnetic equator. This also gives rise to electric fields which perturb the upper region of the ionosphere and cause the Appleton anomaly. The Appleton anomaly consists of a pile-up of electrons in the ionosphere, north and south of the magnetic equator, leaving a deficit just over the equator. Coincidentally, a similar distribution has been reported for atmospheric ozone, which has a minimum over the geographic equator, and maxima at higher and lower latitudes. We are currently negotiating a cooperative program with Italy, called San Marco-D, which will consist of two Scout-launched payloads in equatorial orbit. The first, at low altitudes, will make measurements of the neutral and ionized atmosphere and the electric fields. The second, in a highly elliptical orbit, will make pictorial measurements of cloud velocity, ozone concentration and atmospheric temperature. San Marco-D will, therefore, address itself to the dynamics of the equatorial ionosphere, measure ozone with high time-resolution to complement our other measurements, and search for possible solar-weather relationships by seeing whether these data show any correlations.

We have already indicated that the earth's magnetic field links high latitude locations near the ground to portions of the distant magnetosphere. At Siple, in Antarctica, a powerful very-low-fre-

# MAGNETOSPHERIC EFFECTS FROM GROUND-BASED TRANSMISSIONS

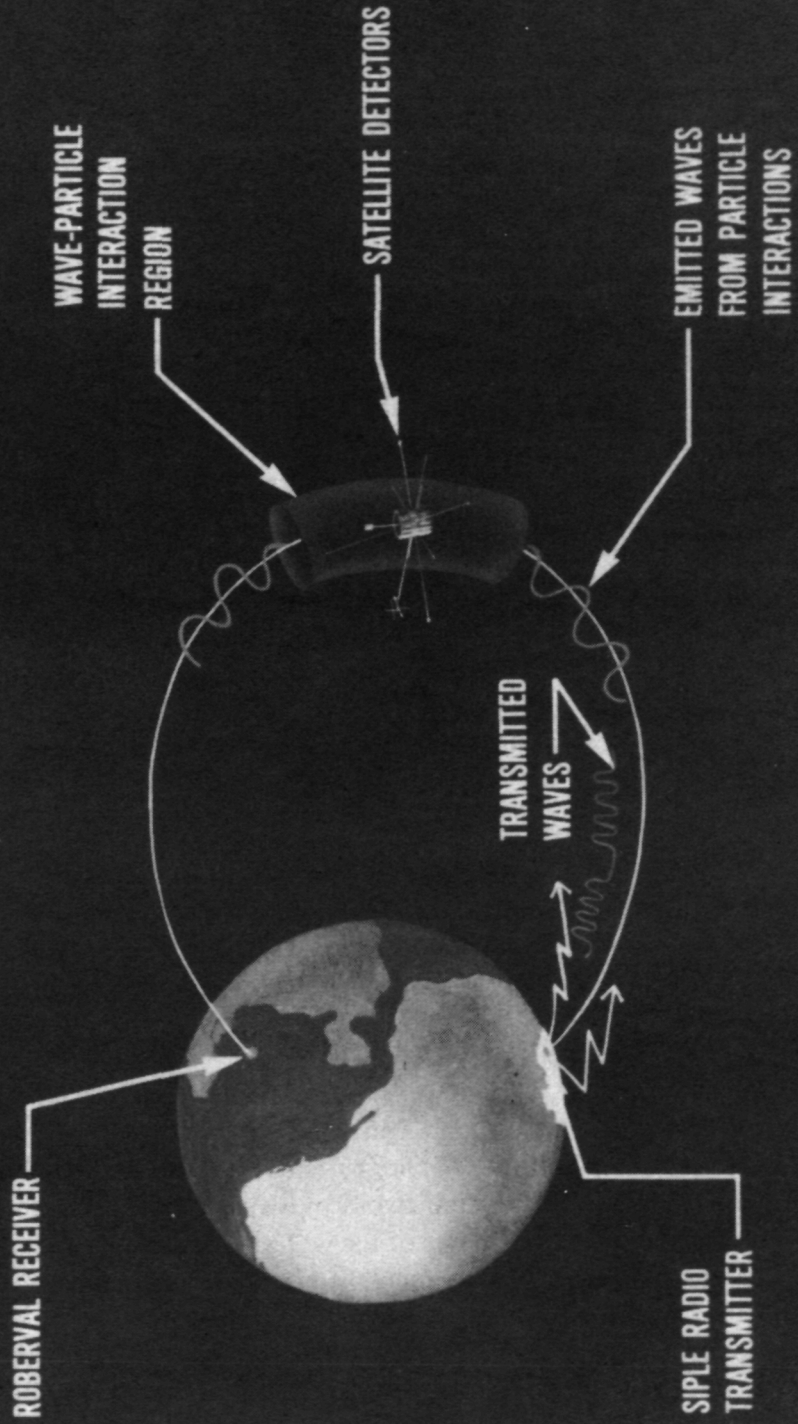


Figure 23.

quency radio transmitter is capable of sending a signal which can produce a measurable perturbation in the magnetosphere. We have already observed the triggering of radio emissions called whistlers, and plan to investigate more closely the interaction of these transmissions with the magnetospheric particles by operating the transmitter in conjunction with detectors on ISEE and EE (Figure 23). These experiments are forerunners of the wave-particle interaction studies we hope to do on the Atmospheres, Magnetospheres and Plasmas-in-Space (AMPS) laboratory on Spacelab, where we can greatly enlarge the interaction possibilities by carrying a radio transmitter into the ionosphere. A whole range of wave-particle interactions are known to be possible, and they are important because they form the basis of particle accelerations, and the sudden release of trapped energy in terrestrial substorms and in solar flares. Indeed, there is already evidence that harmonics of the Canadian power distribution system can trigger the emission of whistlers from high inside the magnetosphere and the precipitation of trapped electrons from the radiation belts.

### Current and Future Programs

The main thrusts which represent our present approach to investigating the nature, origins, and controlling influences on the magnetosphere can be summarized as follows:

*Solar Wind/Magnetosphere Interactions*—These produce the outer boundaries: the shock front, the magnetopause, and the magnetospheric tail. They also result in a flow of “hot” plasma inside the magnetosphere, and a complicated series of electric fields, currents, and plasma flows. The main tool for investigating the major features of these processes is the ISEE (International Sun-Earth Explorer) program. The ISEE-C spacecraft, to be launched in 1978, is intended to measure the details of the incoming solar wind from a position close to the sun-earth libration point, well outside the earth’s magnetosphere. This spacecraft will also provide a platform for measuring cosmic rays. The twin spacecraft, ISEE-A and B, are expected to be launched in late 1977 from a single vehicle into highly elliptic orbits which will be able to sample different parts of the magnetosphere. ISEE-A will be built by NASA, and ISEE-B by the European Space Agency, ESA. The separation of ISEE-A and B will be varied by an on-board propulsion system, so that ISEE-A and B will be able to study the response of the magnetosphere to a known solar wind input, and to provide two samples of the magnetospheric state which will help to distinguish between variations with time and variations with position.

*Solar Photon/Atmosphere Interactions*—These produce the ionosphere, and motions of this “cool” plasma driven partly by the heating of the regions where the energy is absorbed, and partly by the electric fields and currents which result from the atmospheric motions pushing the ionized particles across the earth’s magnetic field. The Atmosphere Explorer (AE-C,D,E) missions are dedicated to investigating these interactions, and have already developed a great deal of new information which is now being studied in detail.

*Magnetosphere/Ionosphere Coupling*—The outer “hot” plasma which moves in the magnetosphere is coupled to the inner “cool” plasma, which tends to co-rotate with the earth, primarily by the electric fields which come from the inner and outer current systems driven, respectively, by the solar photon and solar particle streams. The Electrodynamic Explorer (EE) program which is now being developed is dedicated to these coupling problems, which include the major question of how particles are accelerated from the energies seen in the solar wind to the energies seen in the magne-



tosphere, to the generation of radio waves in the magnetosphere, and the production of cosmic ray particles.

These major thrusts relate the key problems of inter-relationships as depicted in figure 24. Each of these key missions is being implemented by a team of Investigators working closely together who have used the best available information to sharpen the questions which can be asked of nature, and to design their instruments to respond jointly to these questions in the best way. The team effort is needed to ensure, before launch, that the instrumental ranges and the spacecraft orbits are optimized; and after launch, that the requisite data are jointly analyzed to respond to the cause-and-effect problems, with intermediate adjustments during the mission as suggested by the preliminary results—if the data are analyzed and made available with sufficient promptness. The needs of the magnetospheric physics discipline have resulted in a trend away from a Principal Investigator working in isolation on a single problem towards an Investigator team whose members work closely together and bring a variety of special talents and resources to bear on the complex major problems of the interactions which control the earth's environment in space.

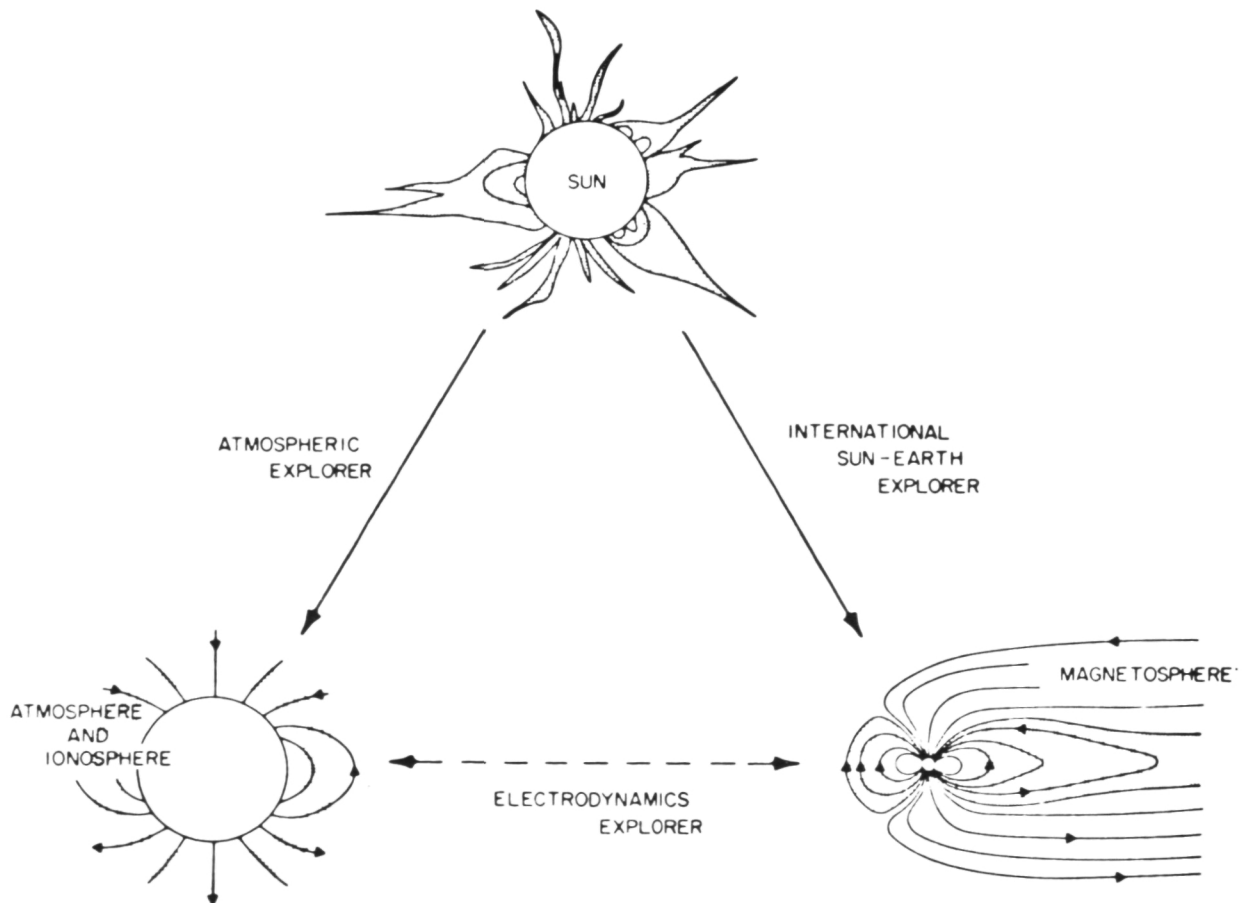


Figure 24. Interrelationships in the earth's space environment and the missions that will address them.

The missions just summarized represent our current major thrusts, but hardly our only efforts. The treasure-house of data obtained from earlier spacecraft is constantly yielding new insights and helping to sharpen the questions for future programs. Smaller scale efforts in the Explorer program are helping to define processes in regions of space not traversed by the major missions. Sounding rockets provide vertical profiles and low-altitude data in conjunction with the geographical coverage provided by the spacecraft, and backscatter radars add time variations at fixed locations which add another, needed, dimension to the tools available for research in the magnetosphere. The International Magnetospheric Study (IMS) represents an organized attempt during the period 1970-1979 to coordinate the effort of many different scientists using a variety of different tools on the ground and in space, and provides the basis for theoretical and modelling studies throughout the scientific community.

### The Space Shuttle Era

The Space Shuttle will make it possible to complement the mainly passive observations of nature discussed in the previous sections by performing active, controlled experiments to study directly the fundamental interactive processes which govern the geophysical and space phenomena identified by earlier programs.

The Atmospheres, Magnetospheres and Plasmas-in-Space (AMPS) Spacelab program which has been the subject of advanced study has identified two major features which Spacelab can add. Firstly, there is the ability to carry the heavy instruments which can introduce a known input, as in a laboratory experiment; and secondly, the ability to carry the heavy instruments to perform remote sensings of the lower atmosphere, and of the response to the stimuli produced by AMPS itself.

It is becoming increasingly apparent that a rich variety of wave/particle interactions play the major roles in governing the key phenomena observed in the magnetosphere. These can be studied directly from AMPS, which will have the ability to inject streams of particles of known characteristics, electromagnetic pulses of accurately defined parameters, and tracers of almost any desired type. The "atmosphere" and "magnetosphere" portions are combined by intent, since the very instruments which can measure excited and minor species in the natural atmosphere are also those required to observe many of the reactions to the on-hand stimuli. The processes which can, in this way, be directly studied pertain not only to the atmosphere and magnetosphere of the earth, but also the atmospheres of other planets and astronomical objects. In this program, an attempt is being made to design the core instruments with a maximum of flexibility, so that, when these become available, the AMPS missions can be readily "retuned" at short notice to the most exciting problems of the 1980's, and be easily available to a large number of users with a minimum of redesign.

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