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SOLAR TERRESTRIAL PROGRAMS

A Five-Year Plan

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Solar Terrestrial Programs Office
Office of Space Sciences
National Aeronautics and Space Administration

SOLAR TERRESTRIAL PROGRAMS
A Five-Year Plan

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Office of Space Sciences
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"Perhaps the strongest area that we face now is the area of solar terrestrial interaction research, where we are still investigating it in a basic science sense: How does the Sun work? What are all these cycles about? What do they have to do with the Sun's magnetic field? Is the Sun a dynamo? What is happening to drive it in an energetic way? Why is it a variable star to the extent to which it is variable, which is not very much, but enough to be troublesome to us? And what does all that mean in terms of structure?

How does the Sun's radiation, either in a photon sense or a particle sense, the solar wind, affect the environment of the Earth, and does it have anything to do with the dynamics of the atmosphere?

We have come at that over centuries, in a sense, as a scientific problem, and we are working it as part of space science, and thinking of a sequence of missions in terms of space science.

At the same time, we know very well that this is a problem which is closely connected to the question of understanding climate and weather, and predicting climate and weather; a set of applications that we would very much like to be able to do better than we do now."

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Robert A. Frosch
NASA Administrator

(From a talk given March 30, 1978
at Goddard Space Flight Center)

</div>

PREFACE

This report is dedicated to the community of solar, heliospheric, magnetospheric and atmospheric scientists, and to the administrators and engineers who share their work. A scientific community is held together by channels of communication—scientific results, for instance, are made known by means of journals and conferences. This report, too, is intended to be a means of communication—to inform members of the solar-terrestrial science community about research plans of NASA in their areas of interest during the coming years. It reviews planned and approved missions, their scientific objectives, instruments and special features, as they appeared in August 1978; it also contains a condensed description of the scientific disciplines, information about Spacelab and an account of the planning process to which new missions are subjected.

The report is structured in two layers. The first two chapters and part of the third contain a brief summary of the program, a quick overview intended for first reading. The rest presents a more detailed description, and an extensive bibliography is appended to guide those who seek even more information. A certain amount of repetition has been deliberately included in order to help those who intend to read only selected parts, with cross reference to the rest of the report.

Special thanks are due to David Stern, whose efforts were responsible for this report. Adrienne Timothy helped shape much of the mission program outlined here and critically reviewed this report as its various parts took shape. In addition, we are grateful to our colleagues at Goddard Space Flight Center and elsewhere, whose advice has guided the writing of this document—Joseph Alexander, Leonard Burlaga, Michael Caan, Robert Chapman, Maurice Dubin, George Gloeckler, Joseph Grebowsky, Richard Hartle, Robert Hudson, Stuart Jordan, Carl Reber, Richard Stolarski and Roger Thomas. Thanks are also expressed to the many individuals and institutions who supplied illustrations and whose names are acknowledged in the appropriate captions.

Harold Glaser
Director, Solar Terrestrial Division
Office of Space Sciences
NASA Headquarters, Washington, DC

Contents

I. INTRODUCTION AND OVERVIEW

The Sun dominates the Earth's environment in many ways. Its light supplies energy to life on earth and to weather processes, its short-wave radiation heats and ionizes the Earth's upper atmosphere, and the constant outflow of hot "solar wind" perturbs the Earth's magnetic field and is responsible for energetic particles in the radiation belt and the polar aurora.

NASA's Solar Terrestrial Division's program aims to study the Sun, the environment of the Earth and the complex chain of interactions between these two. More explicitly, its stated goals are:

1. To understand the generation of energy in the Sun, its transformation into different forms and transport into interplanetary space, and its interaction with the earth's magnetic and atmospheric environment.

2. To understand the physics and chemistry of the upper atmosphere and to detect any global changes in stratospheric ozone.

3. To understand the plasma processes which characterize the Earth's magnetosphere and ionosphere and thereby to provide new insights about other planetary magnetospheres and ionospheres and about high energy astrophysics.

4. To understand the Sun as a star.

As this list demonstrates, solar-terrestrial research has two main motivations:

(1) On one hand, such research leads to a *better understanding of man's environment*. In-situ observations from space provide firsthand information about the solar wind and about the earth's magnetosphere, and remote sensing of the Sun and of the Earth's upper atmosphere yields data which cannot be collected from the ground because of the interference of the atmosphere.

From such information, the processes which determine Solar Terrestrial relations can be studied. Moreover, perturbations affecting our space environment and its interface with the earth can also be traced and understood—for instance, the effect of man-made chlorine compounds on stratospheric ozone, or the effects of solar activity, the 11-year solar cycle and the influence of interplanetary magnetic features on the upper atmosphere and perhaps also on the troposphere.

(2) On the other hand, the environment studied by the solar terrestrial program is the site of many *fundamental processes of astrophysical interest*. The Sun is the only star which can be studied in any detail and thus solar observations aid the understanding of distant stars—for instance, the role of the solar wind in slowing down the Sun's rotation may help explain rotation rates of stars in general.

Furthermore, most of the solar-terrestrial environment is filled with tenuous *plasma*—hot, electrically conducting gas—and large-scale magnetic fields, producing "cosmic" conditions which resemble those of distant astrophysical objects and which cannot be duplicated in the laboratory. Of special interest in such plasmas are processes which impart appreciable amounts of energy to flows of *fast particles*—this happens in the Earth's magnetosphere, especially in violent outbursts known as magnetic substorms, and it also happens on a vaster scale in solar flares, outbursts associated with sunspots and capable of flooding interplanetary space with high-energy particles. Studies of the acceleration mechanisms which produce such particles advance us towards the solution of the basic riddle of high-energy astrophysics—the extraordinary abundance of energetic particles produced in supernovae, quasars, X-ray sources and in the galactic cosmic radiation.

In the 20 years since Explorer I, observations from space have greatly increased our knowledge of the solar-terrestrial environment. In this document, an attempt is made to chart the missions and developments expected in the near future—in particular, *major new projects to be initiated in the 5-year period of FY 1980-1985*. Such planning is important because many areas of solar-terrestrial research have now completed their initial exploratory phase and have advanced to a stage where they require *specific experiments*, bearing on well-defined questions and observations, and requiring careful preparation. In addition, spaceflight missions have grown in size and sophistication, increasing the *lead time* needed for their preparation, which again underlines the need for planning.

It is convenient to divide solar-terrestrial space into 4 regions (described in more detail in chapter IV), as follows:

1. The Sun.

2. The Heliosphere—the region dominated by the solar wind.

3. The Earth's Magnetosphere.

4. The Earth's Upper Atmosphere.

Each of these regions has unique properties and problems, and they all are strongly coupled along their mutual interfaces:

i. The Sun

The Sun is the source of most of the energy reaching the surface of the Earth, and therefore mankind has a natural interest in measuring, monitoring and understanding its radiation, both in the visible spectrum and in the shorter wavelengths which are absorbed in the upper atmosphere. As our *nearest star*, the Sun provides detailed information about convective flows and other properties characterizing the outer layers of a typical star. And finally, there exists *"solar activity"*—transient phenomena related to intensely magnetic sunspots and to explosive energy release events which occur near them. These latter events, *solar flares* (Figure I-1), influence all other regions of the solar-terrestrial environment and appear to be similar to other types of high-energy astrophysical phenomena.

The Sun's overall level of activity rises and falls in a characteristic *11-year cycle*: this cycle strongly affects the upper layers of the earth's atmosphere and could also exert a subtle influence on lower atmospheric levels and thus on our climate. In addition, there exists evidence that at irregular intervals the Sun's activity drops to a very low level (most recently during the *"Maunder minimum"* 1645-1715) and that such periods coincide with times of unusually cool world-wide climate.

ii. The Heliosphere

The outer layer of the Sun, *the corona*, is in a constant state of expansion, filling the space around the Sun with a rapid outflow of hot solar gas, the *solar wind*. This tenuous plasma exhibits a variety of shock waves, high speed streams and discontinuities, and its composition provides important information about the composition of the outer solar envelope.

The solar wind also transmits energy and momentum to the magnetic field of the earth, which stands as an obstacle in its path, and this creates a broad plasma shock wave. The coupling between the solar wind and the earth's magnetosphere provides energy for magnetic storms and substorms, for particles of the radiation belt and of the polar aurora, and for currents which heat the polar ionosphere.

iii. The Magnetosphere

Surrounding the Earth there exists a region where direct entry of the solar wind is prevented by the Earth's magnetic field—*the magnetosphere*. The interface between the solar wind and the magnetosphere contains a number
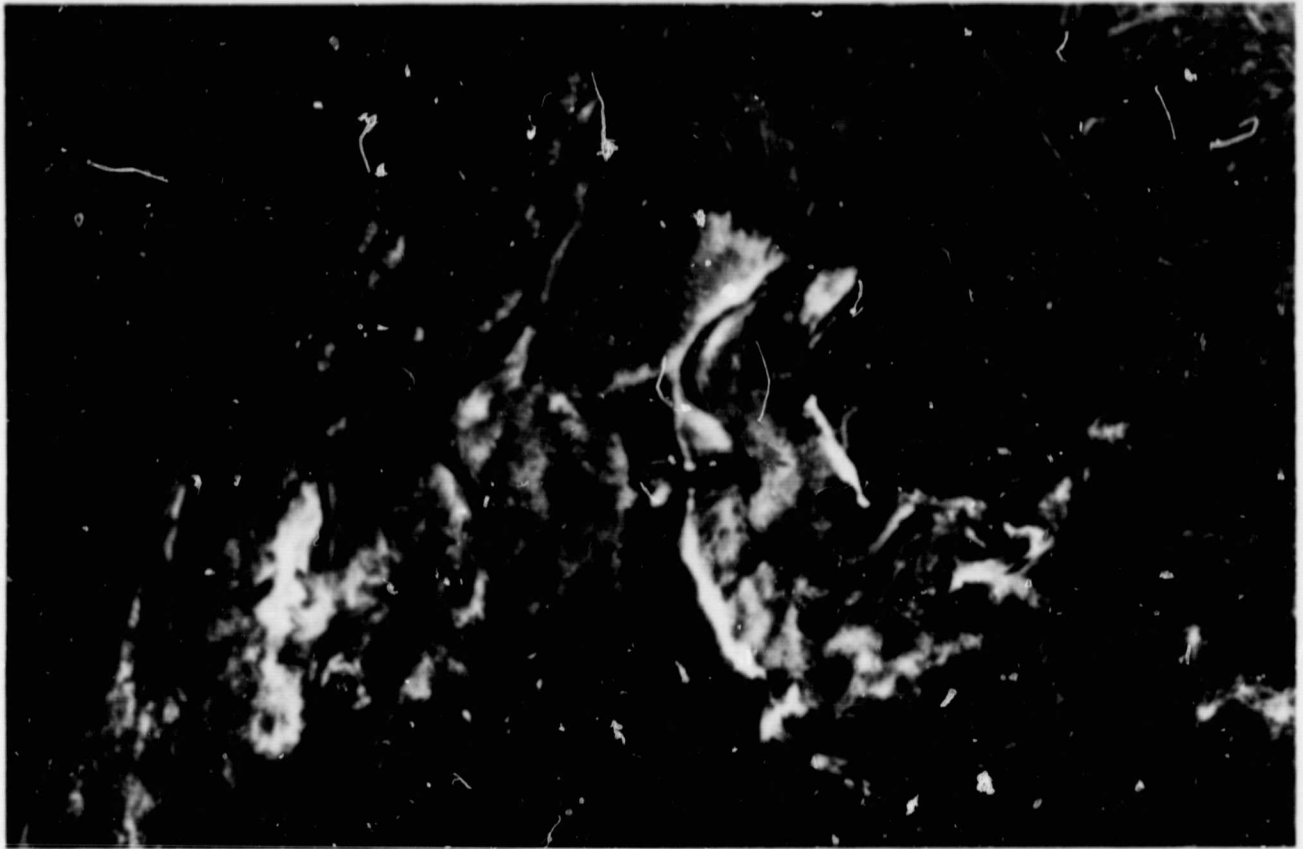
Fig. I-1. Large solar flare (importance 4B) observed 1329 UT, April 28, 1978 (Courtesy Air Force Solar Observatory, Holloman AFB).

of distinct boundary layers, and a direct electric connection appears to exist between the two (probably due to "magnetic merging"), permitting the flow of electric fields, energy and particles from interplanetary space to the magnetosphere. This connection sets up large-scale electric fields and currents in the magnetosphere, involving intricate electrical circuits which can store appreciable energy. Ultimately much of this energy—originating in the solar wind—flows into the high-latitude ionosphere, and electromagnetic forces are also transmitted by this linkage.

Most large-scale features of the earth's magnetosphere have been extensively studied, including the *trapped radiation belt* surrounding the earth and the long *geomagnetic tail* on the night side, containing a layer of hot plasma and extending well beyond the moon's orbit. The magnetosphere is constantly agitated by external influences and it interacts strongly with the ionosphere in which its magnetic field lines are anchored. Several processes observed in it accelerate particles to high energies: such accelerations often take place rather abruptly in a sequence of
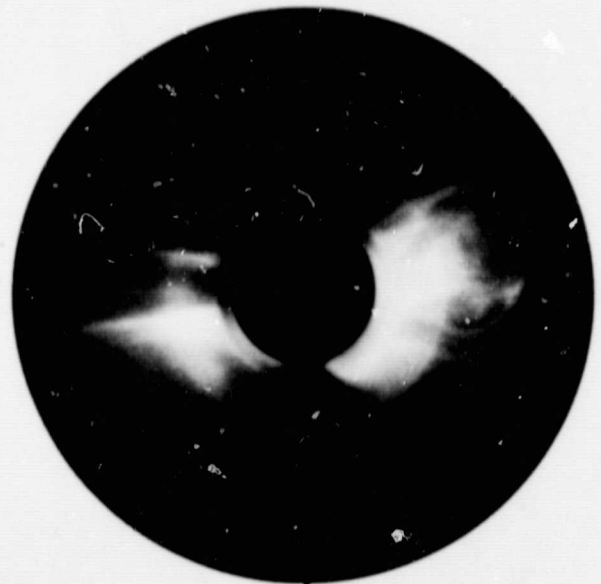
Fig. I-2. The solar corona, as viewed from Skylab on August 10, 1973. An opaque occulting disk with nearly twice the angular diameter of the Sun covers the solar disk. On the left two coronal streamers are visible, while on the right a huge "bubble" or "coronal transient" is being ejected at about 400 km/sec.

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Fig. I-3. A composite view of auroral displays over North America, recorded by a meteorological satellite on April 14, 1974. The lights of several urban areas are identified.

events known as the *magnetospheric substorm*, which shares many properties with flares on the sun. Substorms apparently originate in the magnetotail and are often triggered by certain changes in the solar wind. They create widespread auroral displays (Figure 1-3), magnetic disturbances, radio-wave emissions and particle injections into the radiation belt, and their study represents one of the major challenges of magnetospheric physics.

iv. The Upper Atmosphere

The upper atmosphere is bound to the earth by gravity and may be roughly divided into several layers. The outermost is the *exosphere* where atoms and molecules move in ballistic orbits and experience few collisions. Below this is the *thermosphere*, heated to appreciable temperatures by the shortest wavelengths of the solar spectrum, at rates which vary greatly with solar activity (see Fig. IV-23). Part of this gas (the *ionosphere*) is ionized and is therefore strongly affected by magnetospheric currents and particles, which deposit in it considerable amounts of energy, especially in polar regions. The ionosphere exerts a strong influence on the propagation of radio signals between stations on the ground.

Lower down, the *mesosphere* and *stratosphere* (jointly known as the "middle atmosphere") absorb the bulk of the solar ultra-violet radiation flowing towards the Earth; ozone, a relatively minor constituent, plays a dominant role in the processes of absorption, heating and re-radiation. Complicated chemical reactions and flow patterns characterize this region and small concentrations of active substances (natural or man-made) can strongly influence them. It is anticipated that in the 1980's Spacelab and the Upper Atmosphere Research Satellite program will add much to our knowledge of these two layers, most of which are too high for balloons and too low for direct sampling by satellites.

The 5-year plan described below outlines the plans of the Division of Solar Terrestrial Programs in NASA's Office of Space Science for future activities related to its goals. It:

— *reviews the scientific disciplines* involved and their outstanding problems,

— *lists principles* and considerations which have guided the evolution of this plan, and

Fig. 1-4. A view of the Earth in ultraviolet light (1250-1600 A), taken from the lunar surface by the far-UV camera of the Naval Research Laboratory. This view differs from Figure IV-24 in that it excludes the bright spectral line of hydrogen at 1216 A. The dayside hemisphere reflects bright sunlight, but on the night side two airglow bands are visible, symmetric with respect to the magnetic equator; it is believed that they are emitted by atomic oxygen in the upper atmosphere. A bright patch also appears above the auroral zone which faces away from the Sun (picture courtesy of G. Carruthers).

— *describes existing and proposed space flight missions* and other relevant scientific efforts.

To be useful a plan must be both comprehensive and flexible: some of its proposed actions may be delayed or modified by contingencies, while others may be accelerated or changed by unexpected discoveries or opportunities, or by new needs. Thus it may be expected that this plan will be continually updated in the future: the present effort is itself a revision of an earlier plan, released January 1977. Comments or suggestions concerning the future course of NASA's solar terrestrial program, for use in further revisions of this document, are welcome and should be submitted to the Director of Solar Terrestrial Division, mail code ST, NASA HQ, Washington, D. C. 20546.

II. MISSIONS AND PROGRAMS

The missions and programs to be launched or started during the next 5 years are relevant to the central problems of all areas included in the Solar Terrestrial Program:

In *solar physics*, accent is placed on active solar phenomena, especially on solar flares (SMM, SCADM, Spacelab solar instruments and Pinhole Camera satellite).

In studies of the *heliosphere*, emphasis is on the exploration of new regions (Solar Polar Mission, Solar Probe).

In the *magnetosphere*, interest is focused on processes which transfer energy and particles from the solar wind to the earth, and increasing use is made of coordinated observations from several spacecraft (ISEE, DE, OPEN). In addition, active experiments are to be performed in the earth's plasma environment (AMPTE, AMPS).

In the *upper atmosphere* the main attention is on the dynamics of the middle atmosphere, on the production, flow and loss of its active constituents such as ozone and on their interaction with short-wave solar radiation (SME, UARS, Spacelab).

Among planned spaceflight missions one may distinguish three types:

(1) "Observatory Class" missions—large free-flying observatory satellites or systems of such satellites.

(2) "Explorer class" missions—smaller and less expensive, often with a more narrowly defined objective.

(3) Spacelab missions—manned missions using the Space Shuttle and the Spacelab orbiting laboratory.

Each free-flying mission first undergoes a comprehensive study. If the results are encouraging, proposals for experiments are solicited, Agency, Executive Office and Congressional approval is requested and if obtained, the spacecraft is built and launched, and its data are collected and analyzed. This process is discussed in more length in section IX-b.

Given below is a list of approved and of planned missions: the latter ones (Table II-1) form the core of this 5-year plan and represent projects for which the Solar Terrestrial Program is seeking approval in the FY 1980 1985 period. More details about these missions are spelled out further along in this document, as noted in the table of contents.

a. Observatory Class Missions

APPROVED

Solar Maximum Mission (SMM; Launch 1979): a solar observatory in near-earth orbit, designed primarily to observe solar flares in ultraviolet (UV), extreme ultraviolet

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(XUV) and X-rays, with much finer resolution than prior observations of this type.

Solar Polar Mission (SPM; Launch 1983): dual spacecraft passing high above the northern and southern polar regions of the Sun and providing initial data about the solar wind, interplanetary magnetic field and cosmic radiation in these regions, hence giving the first 3-dimensional view of the heliosphere.

The Solar Polar Mission is an international venture undertaken jointly with the European Space Agency (ESA), which has the direct responsibility for one of the two spacecraft. Both spacecraft will pass near Jupiter and will use its gravity field to attain trajectories which rise far outside the orbital planes of the Earth and other major planets.

PROPOSED AND UNDER STUDY

Upper Atmosphere Research Satellite program (UARS — start 1981, launch 1983-4): two satellites (possibly followed by additional ones) with remote sensors measuring active constituents, temperatures and other dynamic variables characterizing the middle atmosphere (stratosphere, mesosphere and lower thermosphere). UARS will measure the density of the ozone layer and assess various processes which affect it, including man-made perturbations. Its observations, together with those of Spacelab, will also permit an assessment of the influence of solar activity and magnetospheric processes on the upper atmosphere, effects which may well be the key to Sun-weather coupling.

Origin of Plasmas in the Earth's Neighborhood (OPEN — start 1982, launch 1985): a comprehensive study of the Earth's magnetosphere by a network of spacecraft, designed to trace the flow of particles and energy from the solar wind to various magnetospheric regions and to the upper atmosphere. As currently planned, OPEN contains 4 spacecraft—an Interplanetary Plasma Laboratory (IPL) permanently placed in the solar wind, a Geomagnetic Tail Laboratory (GTL), an Equatorial Magnetosphere Laboratory (EML) in the ring current region and a Polar Plasma Laboratory (PPL) in an elongated polar orbit. GTL will investigate the yet-unexplored distant geomagnetic tail beyond the moon's orbit, using lunar gravity swing-by maneuvers to modify its motion; EML, using its onboard propulsion, will join it in that region later in the mission. PPL will also use its propulsion to vary the eccentricity of

its orbit, enabling it to explore both the polar cusps on the boundary of the magnetosphere and the region of "parallel electric fields" several earth radii above the auroral zones.

Solar Cycle and Dynamics Mission (SCADM — start 1983, launch 1985): a solar observatory of a size similar to that of SMM, but designed to observe the Sun between peaks of solar activity. SCADM is expected to provide information about the quiet-time corona, magnetic field and solar surface waves, and it has particular significance because simultaneously the two Solar Polar spacecraft will be viewing the Sun from completely different directions.

Table II-1

Office of Space Sciences
SOLAR-TERRESTRIAL PROGRAM
FY 1980 PLAN
FLIGHT PROGRAMS

	New Start FY	Launch FY	Responsible Field Center
Solar Polar Mission	1979	1983	JPL
Spacelab Multi-user Instrument Program	1979	1983	GSFC, LaRC Ames
Upper Atmosphere Research Satellite (UARS)	1981	1983	GSFC
Origins of Plasma in Earth's Neighborhood (OPEN)	1982	1984	GSFC
Solar Cycle and Dynamics Mission (SCADM)	1983	1985	GSFC
Solar Probe	1983	1986	JPL
Pinhole Satellite Mission	1984	1987	MSFC
Solar Terrestrial Observatory	1984		MSFC

Solar Probe (Start 1983—launch 1986): a spacecraft designed to approach within 4 solar radii of the Sun and to perform observations of the solar wind near its source, in particular, to study the way the solar wind is energized. This mission will also perform measurements relevant to the general theory of relativity and to the possible existence of a rapidly rotating solar core. To achieve its un-

usual orbit the Solar Probe will require an appreciable velocity boost, and this may be provided either by an encounter with the planet Jupiter or by means of an ion engine.

Pinhole Camera Mission (Start 1984–launch 1987): a solar study using a satellite with X-ray and gamma-ray sensors, together with a large shield, orbiting separately some distance away and obscuring most of the Sun from the satellite's view; the shield will probably be carried aboard the Space Shuttle in a polar orbit in the dawn-dusk plane. A multiple pinhole array in the shield will make possible high-resolution studies of flare regions in hard X-rays and gamma rays, which are the characteristic signatures of high-energy particles produced in such events.

b. Explorer Class Missions

APPROVED

Dynamics Explorer (DE; launch 1981): a dual spacecraft mission. The first spacecraft is in a low polar orbit and observes electrodynamic phenomena, energetic particles and properties of the upper atmosphere, with special emphasis on the polar and auroral regions. The second spacecraft shares the same orbital plane but has an apogee of several earth radii, enabling it to observe auroral phenomena from a distance (compare Fig. I-3) and to measure effects of "parallel electric fields". This dual mission is expected to provide new insight about the coupling between the atmosphere, ionosphere and magnetosphere.

Solar Mesosphere Explorer (SME; start 1978, launch 1981): a spacecraft measuring key properties of the stratosphere and mesosphere through the atmospheric absorption of sunlight during "sunrise" and "sunset" as viewed by the satellite. Solar ultraviolet radiation will also be monitored, in order to determine how its changes affect the behavior of the middle atmosphere.

Active Magnetospheric Particle Tracer Experiment (AMPTE; start 1980, launch 1982): a dual spacecraft mission, conducted jointly with the Federal Republic of Germany. A special module orbiting the earth at large distances will release tracer clouds of lithium and europium vapor, in the solar wind just upstream of the Earth's magnetosphere and again in the magnetospheric tail. A Charge Composition Explorer (CCE) spacecraft closer to the Earth will attempt to detect ions from the release. The principal objective of the mission is to determine the manner in which the released ions enter the magnetosphere (simulating the entry of solar wind particles) and the extent to which they are accelerated there.

c. Spacelab Missions

The Spacelab orbiting laboratory used aboard the Space Shuttle (Figure II-1) is described more fully in sec-

Fig. II-1. An artist's cut-away view of the Shuttle/Spacelab in orbit, showing the laboratory module, the tunnel linking it to the cabin of the Shuttle and two pallets with instruments. Cargo bay doors (not shown) enclose the payload during launch and reentry.

tion VII-3 and in chapter VIII. Spacelab, a joint project of NASA and of the European Space Agency (ESA), is scheduled to begin flights in mid-1980 and will undertake sorties lasting 7-28 days.

Spacelab payloads considered in this plan belong to one of two types: "facilities" capable of accommodating different users, and "principal investigator experiments" handled by individual research teams. Some of the larger instruments described below will be "facility type", others may start in the PI mode and could later evolve into facilities. Two groups of such instruments are currently planned:

(1) *Solar Instruments*, including three large instruments designed to observe the short wavelengths characteristic of high-energy and high-temperature solar phenomena:

   i. The *Solar Optical Telescope* (SOT) a telescope with a 125 cm mirror capable of high resolution in both the visible range and in the ultraviolet. The mirror will be held by a large truss which can accommodate several solar instruments—some of them taking turns in using the large mirror, others (possibly including GRIST—see below) sharing the pointing system but operating independently.

   ii. An *Extreme Ultra-Violet* (XUV) *Telescope*, utilizing grazing-incidence mirrors—e.g. GRIST, developed by the European Space Agency (sect. VIII-c-2). By arranging for all reflections of rays to occur at shallow angles, good optical resolution may be obtained in the wavelength range 100-1700 A.

   iii. A *Hard X-ray Imaging Instrument* (HXII, read "Hixie"), using an array of absorbing grids to resolve solar features which emit hard X-rays, in the energy range from 2 to 80 keV.

In addition to these facilities, a number of smaller "PI type" solar experiments are envisioned, with special emphasis on "quick reaction" experiments which can be flown at short notice should the Sun become unusually active.

(2) The *Atmosphere, Magnetosphere and Plasmas in Space* (AMPS) program, which encompasses two classes of experiments:

Atmospheric Physics—some of the facilities are:

   i. A *Lidar* (Light Detection and Ranging) facility, using several powerful lasers. Radiation backscattered from atmospheric molecules or aerosols will be studied to determine the constitution and other properties of the upper layers of the Earth's atmosphere.

   ii. A *Cryogenic Limb Scanning Interferometer and Radiometer* (CLIR—see sect. VIII-d-2) or a similar instrument, for remote sensing of infra-red emissions of the middle atmosphere. Cryogenic cooling (e.g. by liquid helium) greatly extends the sensitivity of such instruments, making them suitable for studying a large number of active constituents including ozone (O_3), NO, H_2O and even man-made pollutants such as chlorofluoromethanes.

Space Plasma Electrodynamics experiments and facilities include:

   i. A *Wave Injection Facility* (WIF) which would generate electromagnetic waves, study their propagation and use them to probe local plasma conditions or even to initiate active experiments which temporarily modify the environment. A retrievable subsatellite carried by the Shuttle would act as an independent remote detector in many such experiments.

   ii. *Chemical Releases* of barium vapor, lithium vapor or other substances can temporarily modify ionospheric conductivity, precipitate natural trapped particles, generate gravity waves and perform other active modifications. A Chemical Release Module (CRM) launched from the Shuttle could carry out such releases at selected distances and times (even over a time span of months) and the particles could also serve as magnetospheric tracers, as is already envisioned for the AMPTE mission.

   iii. *Electron Accelerator Beams* have a variety of uses, e.g. probing voltage drops along magnetic field lines, exciting plasma instabilities by the motion of the beam through the ionospheric plasma, the generation of artificial auroras and the large-scale tracing of magnetic field lines.

In addition to the major projects listed above, the Solar Terrestrial Program of NASA plans to continue its major

involvement n "Science-Research-Technology" (SRT) funding, coordinating this task with other sources of support, e.g., the National Science Foundation. Such supporting activities are important because they complement spaceflight missions, extract additional knowledge from space data, involve large segments of the scientific community in space missions and integrate results obtained from space with existing scientific knowledge and with other observations. Types of related research include:

(1) *Theoretical Studies* involving physical explanations of observed phenomena (and at times, the prediction of phenomena not yet observed), models of the environments of the Sun, interplanetary space, the Earth's magnetosphere and the upper atmosphere, and models of processes which take place within and between these regions.

(2) *Development of new instrumentation*, to advance the technology used by spaceflight missions. For instance, the infra-red sensors and pulsed lasers scheduled to be used by Spacelab (chapter VIII) will have completed extensive development before they are placed in space.

(3) *Observations from the ground, aircraft, balloons and sounding rockets* all provide valuable support to space missions. Ground facilities include networks of ground magnetometers, solar observatories on the ground and ionospheric radars and sounders. Aircraft, balloons and rockets serve not only as platforms for observations above the major part of the atmosphere, but also as test vehicles in which new instruments may be checked out and calibrated before they are placed aboard orbiting spacecraft.

(4) *Analysis of data* returned from space. As the volume of such data increases, their proper preparation, analysis and mutual correlation require increasing attention, as do their archiving and their distribution to scientific users.

(5) *Communication of results*, of data and ideas. This is supported mainly through scientific journals, workshops, conferences and reviews.

III. GUIDING PRINCIPLES

In assembling this 5-year plan, certain guiding principles were recognized:

a. Technical and Scientific Merit

Care was taken to assure that the plan was *technically sound.* A 5-year plan is not an is^lated entity, but a segment in a continuing effort: it should rely on understanding and expertise obtained earlier to define problems and missions in which any effort invested promises to yield the best return.

A few "reconnaisance" missions to explore new regions still exist—notably, the Solar Polar mission, the Solar Probe and explor. ion of the distant geomagnetic tail (in OPEN). In most areas of the Solar Terrestrial Program, however, a foundation of understanding already exists and this allows new missions to be focused on well-defined observations relevant to key problems—e.g. XUV and hard X-rays from solar flares, ion composition in the solar wind and in the radiation belt and selected chemical constituents of the upper atmosphere.

b. Practical Applications

Tasks which provide an opportunity to help solve problems of *practical importance* are awarded a special priority. These include:

i. The 11-year cycle of solar activity and its impact on the earth's environment. In a broader sense, the

planned missions are expected to help correlate changes in the earth's atmosphere and magnetosphere with solar activity in general and with related effects such as the stream and sector struct re of the interplanetary medium.

ii. Variations of the solar energy output and its spectral composition will be monitored as accurately as possible.

iii. Ozone and other minor constituents of the high atmosphere will be studied and their interactions will be investigated. Such constitutents play an important role in shielding the earth from UV; they also control the temperature of the middle atmosphere, which in turn effects its flow, with possible effects upon layers closer to the ground.

c. Ties to other Disciplines

Tasks in which the Solar Terrestrial Program interacts with *other fields of science* are given special attention— e.g. with astrophysics and plasma physics. Results of our program which may interest scientists in such fields are made available to them and vice-versa—relevant techniques and results from such fields (experimental and theoretical) are freely adapted to the solution of problems in solar-terrestrial physics.

As an example, studies of "the sun as a star" have a great impact on astrophysical models of stars, the dis-

covery of the solar wind has led to new ideas about "stellar winds" and about loss of rotational momentum by stars, and the propagation of energetic solar-flare particles through the interplanetary magnetic field serves as a model for cosmic-ray propagation in the galaxy.

A unique relationship exists between the Solar Terrestrial Program and *plasma physics*, since most of the solar-terrestrial environment consists of plasma—of hot gas, ionized to such a degree that it may be considered as an electrical conductor. Furthermore, because this plasma has low density and large dimensions, it resembles the type of plasma encountered in astrophysics far more closely than does any plasma produced in the laboratory. Thus the earth's collision-free bow shock, magnetic merging and particle acceleration in magnetospheric substorms and voltage drops along auroral field lines (all of which are described in more detail elsewhere in this document) may serve as guides towards a better understanding of high-energy astrophysical processes in general.

Plasmas may behave as fluids and contain rather complicated particle distributions, magnetic field configurations, wave notions and instabilities. Because plasmas occur so commonly in nature and yet possess this inherent complexity, plasma physics is still one of the frontiers of science. On earth, plasma devices are being developed as tools for achieving controlled thermonuclear reactions to provide fusion energy, while in space plasma physics is related to many fundamental phenomena. In order to assess the future of space plasma physics, the Space Science Board of the National Academy of Sciences appointed in 1976 a *Study Committee on Future Objectives of Research in Space Plasma Physics*—referred here (for brevity) as "The Colgate Committee", after its chairman Dr. Stirling Colgate.

The report of the committee was released in 1978 and it concluded that studies of the Solar-Terrestrial environment are essential in advancing plasma physics. It singled out 6 areas in which, it felt, the most significant contributions of this sort can be made:

(1) Magnetic field reconnection ("magnetic merging")

(2) The interaction of turbulence with magnetic fields

(3) The behavior of large scale flows of plasma and their interaction with each other, and with magnetic and gravitational fields.

(4) Acceleration of energetic particles

(5) Particle confinement and transport

(6) Collisionless shocks.

The reader is referred to the full report (ref. 11-3) for complete details and for the rest of the committee's recommendations and findings. It will only be noted here that the 5-year plan of the Solar-Terrestrial Program has aligned its proposed research, where appropriate, with the committee's recommendations.

d. The Space Shuttle

The plan recognizes that the Space Shuttle and the Spacelab orbiting laboratory carried by it are major tools for placing large recoverable payloads in earth orbit, and for allowing their operation to be supervised by an onboard crew.

Details about Spacelab and its uses are given in section VI-3 and in a more detailed fashion in chapter VIII.

e. The Phase of the Solar Cycle

The solar-terrestrial environment undergoes extensive changes in step with the 11-year cycle of solar activity, described in more detail in the section on solar physics. The timing of missions in this 5-year plan therefore must take into account the expected level of solar activity.

Observations of solar flares and of the "hard" radiation associated with them is thus best conducted near the time of solar maximum: the *Solar Maximum Mission* is planned to take advantage of the projected activity peak of 1980, while the *Pinhole Camera* X-ray satellite is scheduled for the time when solar activity rises towards the next maximum after that.

When observing the solar wind, magnetosphere, ionosphere and upper atmosphere, information is needed for both solar active and solar quiet times, to establish the impact of the 11-year cycle on these regions. In addition, different types of phenomena may be studied at different parts of the cycle—e.g. fast solar wind streams near solar minimum and thermospheric heating near maximum.

f. Efficient Use of Resources

The plan is designed *to use technological resources efficiently*, and there exist several ways of achieving this.

i. Frequently *existing sensors* may be exploited to yield significant new information. Several reasons may make this possible:

they may have only been used in restricted parts of space (e.g. sensors for electric fields in the earth's magnetosphere),

they may not yet have achieved their highest possible sensitivity and resolution (e.g. mass spectrometers in the magnetosphere and the solar wind), or

their usefulness can be extended by using them synergistically (e.g. high-resolution instruments for observing solar flares on the Solar Maximum Mission, controlled in such a way that if one of them observes an interesting event, others are steered to view it as well).

ii. *New sensors* and techniques are being developed and introduced, enhancing our observational capability and maintaining the role of the national space program in spearheading technological innovation. They include:

— Lidar and IR heterodyne detectors for upper atmosphere studies.

— Plasma wave propagation experiments making use of retrievable subsatellites launched from Spacelab.

— Two-dimensional photoelectric detectors, to replace photographic film in recording the images obtained from solar telescopes and other instruments. Several types of such detectors are under development ("microchannel plates", "charge coupled devices" etc.) and they excel in sensitivity, in the range of brightness which they can accurately record and in the fact that they encode the image in digitial form, which is readily analyzed by computers.

All these components of the 5-year plan involve technological improvements which appear to be both feasible and scientifically rewarding.

iii. To allow different users to share large instruments aboard Spacelab some such instruments are designated as *"facilities"*. Facility instruments are specifically designed to accommodate multiple users: for instance, the large Solar Optical Telescope (SOT) will be mounted on a truss permitting up to 6 different instruments to alternate in using its 125 cm mirror during any single flight. Of course, a different set of instruments may be used on each flight.

iv. Economical use of resources also implies *making the best use of data*. On-board treatment of data, the efficient merging of results from different experiments on the same spacecraft (together with time, location and attitude), better data systems on the ground, the free sharing of useful information and its proper archiving in data centers all these will be considered in the proposed missions as means for enhancing the usefulness of observations. The availability of NASA's *Tracking and Data Relay Satellite System* (TDRSS) is expected to help extend our data handling capacity in the 1980's.

v. Data from space will be supplemented wherever possible by ground-based observations and by data from balloons and sounding rockets.

g. Use of Theory

The 5-year plan recognizes that progress is most likely when close ties exist between theory and observational missions.

Ideally, observations are guided by theoretical models, their results are used in testing such models and from the comparison there ultimately emerges a better theory, or at least more confidence in the existing one. The Colgate Committee (see "Ties to Other Disciplines" above) singled out this special role in its third recommendation:

"The theoretical component of the space plasma physics effort needs to be strengthened by increased support, and most particularly, by encouraging theory to play a central role in the planned development of the field."

Theoretical knowledge develops in different ways than observations. Its intrinsic cost tends to be relatively low, but it requires time and effort by trained scientists, not just in developing it but also in transmitting it and making it understandable and useful to those who might apply it successfully. Theory has its own specific tools and technology—e.g. computer models (which are extensively used in studying the stratosphere and mesosphere), the theory

of plasma waves and plasma turbulence which have been widely applied in the earth's magnetosphere, and the theory of atomic energy levels and collisional cross sections, indispensible in studies of the chromosphere and corona and of the upper atmosphere.

Above all, theory must be closely linked to observations. The Solar Terrestrial Program encourages such links by supporting "interdisciplinary scientific investigators" on mission teams and "guest investigators" utilizing data after the mission has been established. A special funding category for the support of theory in solar terrestrial physics is being planned.

h. Interfaces

The 5-year plan divides the Solar Terrestrial Program somewhat arbitrarily into 4 areas, but it should be realized that these overlap along broad *interfaces*. The solar corona blends into the solar wind, the earth's bow shock relates to both the magnetosphere and the solar wind, and the electric currents and energy flow of the magnetosphere are strongly coupled with the ionosphere.

Interfaces are critical regions in the scheme of our observations. For example, observations of the ionosphere-magnetosphere interface supply the proper boundary conditions for models of ionospheric behavior, even before a complete understanding of relevant magnetospheric phenomena is achieved. Because of this key role of interfaces, special attention is devoted to them in the 5-year plan.

As a corollary, the strong links between different parts of the solar-terrestrial environment, through their mutual interfaces, make it essential that no areas in the Solar Terrestrial Program should be allowed to lag behind others, or to move far ahead of the rest. This, too, has been one of the underlying principles of the 5-year plan.

i. Relation to other Programs of NASA and of other Agencies

The 5-year plan notes the existence of interfaces between the Solar Terrestrial Program and other NASA programs, and will try to promote mutual benefits wherever such a relationship exists.

For instance, studies of the upper atmosphere and of outside sources which supply it with energy and momentum are relevant to general atmospheric dynamics, investigated by NASA's *Space and Terrestrial Applications Program*. That program may also require information about various manifestations of solar activity and about ways in which the sun may influence the earth's environment (e.g. variability of the solar constant), all of which are to be observed as part of the current plan.

NASA's *Planetary Program* will benefit from studies of processes occurring in the earth's magnetosphere and ionosphere, as models for the behavior of magnetospheres and ionospheres of other planets. The numerous connections between the research outlined here and NASA's *Astrophysics Program* have already been listed in item 3 of this section, under "Ties to Other Disciplines."

Mutual benefits can flow in both directions. Upper atmosphere research has obtained much useful information from studies by the Applications Program (e.g. data from Nimbus spacecraft), while space probes en route to distant planets have observed the solar wind at large distances from the Sun. This collaboration and cross-flow of information is expected to continue during the 5-year period covered here.

In addition, this plan recognizes the efforts of other organizations concerned with the study of the solar-terrestrial environment. The USAF, for instance, was the first to explore the region of auroral "parallel electric fields" by means of the S3-3 spacecraft, has provided valuable observations of the polar aurora from space (see Figure I-3), has developed infra-red sensing technology of which CLIR is an outgrowth (sect. VIII-d-2) and is developing the sophisticated SCATHA mission for studies of electric charging by spacecraft in the magnetosphere. The U.S. Navy's efforts include "Triad", which has performed the first thorough survey of electric current flow along magnetic field lines in the magnetosphere, as well as the many notable contributions of the U.S. Naval Research Lab (see Figures I-4 and IV-24). The National Oceanic and Atmospheric Agency (NOAA) has supported a strong research team concerned with the Earth's magnetosphere and has conscientously collected and disseminated regular observations from the ground of solar and geomagnetic activity. The Solar Terrestrial Program will seek to continue to interact with the scientific programs of the defense agencies and of NOAA, and expects that some of their scientific teams will participate as experimenters on missions described in this report.

A special relationship exists between NASA and the European Space Agency ESA. In the Solar Terrestrial Program this relationship is most strongly expressed in the Spacelab project, which is a shared venture of the two agencies, and in the related set of facility-type instruments (chapter VIII). Other programs shared with ESA include the International Sun-Earth Explorer mission (ISEE) and the Solar Polar Mission, and future joint efforts may well extend this list. Collaborative efforts on a more limited scale exist with Canada (the Shuttle's remote manipulator boom and possibly the Spacelab Wave Injection Facility), the Federal Republic of Germany (AMPTE) and Japan (the Spacelab electron accelerator experiment).

j. Responsiveness to the Science Community

The 5-year plan is intended to serve the science community and must therefore pay close attention to its expressed needs. The major sources of input from the science community into the Solar Terrestrial Program are the *Space Science Board* (SSB) of the National Academy of Sciences (NAS) and the various study committees commissioned by the SSB, e.g. the Colgate Committee described earlier. Recommendations from other committees convened by the National Academy of Sciences, from the Academy's Geophysics Research Board and from consulting committees set up by NASA were also taken into consideration in assembling this plan.

Below are some of the documents in which such recommendations were expressed (further details about them, as well as additional study reports, may be found in the bibliography):

Report on Space Science, 1975 (NAS)

Scientific Uses of the Space Shuttle (SSB, 1974)

Space Plasma Physics: The Study of Solar System Plasma (NAS, 1978)

Halocarbons: Effects on Stratospheric Ozone (NAS Panel on Atmospheric Chemistry, 1976)

Chlorofluoromethanes and the Stratosphere (NASA workshop, August 1977)

Report of the Solar Astronomy Task Force (Federal Council for Science and Technology, June 1975)

The Upper Atmosphere and Magnetosphere (NAS Geophysics Study Ctee., 1977)

As stated in the introduction, comments and suggestions concerning this plan are welcome, and they will be considered along with other inputs whenever it is updated. Please address your communication to the Director, Solar Terrestrial Division, Mail Code ST, NASA Headquarters, Washington, D. C. 20546.
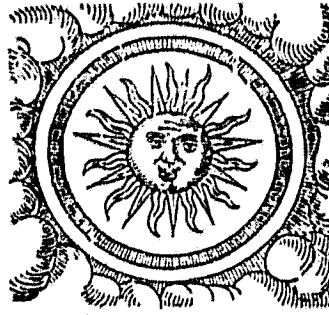
Fig. IV-1. 16th century view
of the Sun

IV. THE SCIENTIFIC DISCIPLINES

Fig. IV-2. A cut-away model of the Sun's interior and envelope
(not drawn to scale). From Gibson, reference 22-1.

a. The Sun

The Sun is our *nearest star*. We can study its surface in great detail and observe on it astrophysical phenomena which on more distant stars remain undetected or unexplained. Thus solar research is the key to many processes in the distant universe.

But in addition, the Sun is also a very special star, *providing the energy* needed to sustain life and to maintain habitable conditions on Earth. If its energy output varied even by a few percent either way, the effect on our climate and on life on Earth would be profound.

The Sun's energy is believed to be generated by thermonuclear fusion of hydrogen, the main solar constituent, deep in its core (Figure IV-2). This energy requires on the average about 1,000,000 years to be transported to the solar surface, from where most of it is radiated into space in the form of visible sunlight. The overall energy flux density reaching the Earth, the so-called *solar constant*, averages 1367 ± 7 watt/m^2 (1976 measurement) and our climate depends sensitively on its value. Continuous monitoring of the solar constant during the present century has disclosed no observable fluctuations but more accurate observations from space are highly desirable (see sect. IV-d-4).
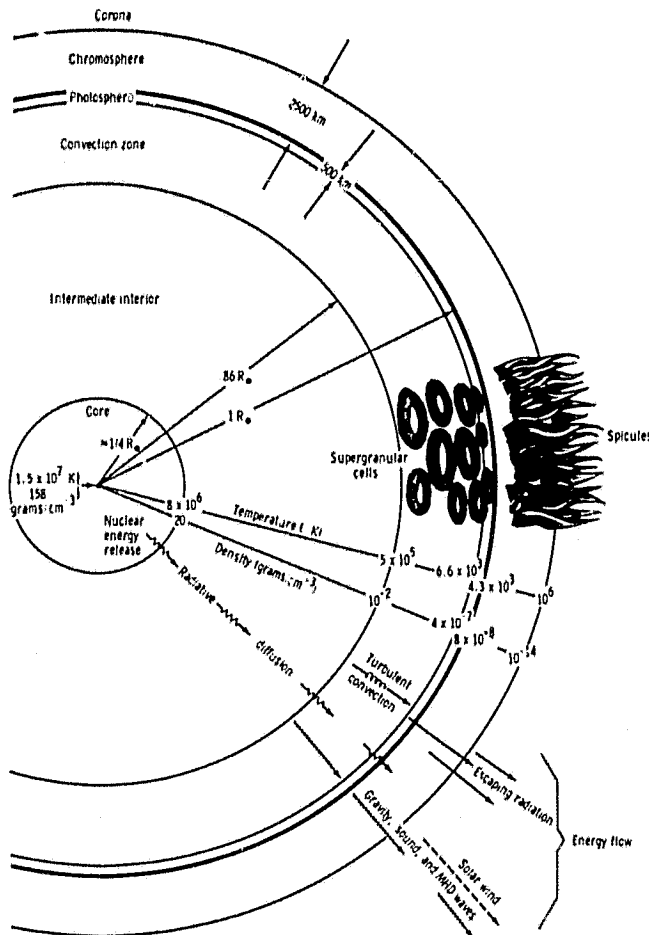
A superficial examination would classify the Sun as a uniformly glowing sphere with a visible radius close to

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700,000 km and an equatorial rotation period of 25.3 days (about 27 days when viewed from the moving Earth). Most of the Sun's light originates in a layer about 500 km thick, the *photosphere*, the spectrum of which suggests an emission temperature of 5780 K. Located above this layer is the *chromosphere*, having a thickness of about 2500 km and a temperature of the order of 10,000 K, and beyond that extends the *corona*, very tenuous and extremely hot: these regions can best be observed either during a total solar eclipse or by using filters which isolate selected narrow regions of the Sun's spectrum. From such indications as spectral lines of iron ionized 15 times the mean energy of particles in the corona is estimated to correspond to a temperature of about 10^6 K. The corona itself has no well-defined outer boundary and blends continuously with the *solar wind*, further described in the section on the heliosphere.

Superimposed on this spherically-symmetric, constant-in-time model of the Sun are the local and variable features with which most of solar research is concerned (Figure IV-3). Although such features have been extensively studied from the ground, observations from space such as those proposed in this 5-year plan have two significant advantages:

First, the shimmering of the atmosphere prevents ground level telescopes from resolving small details on the Sun: only during good observing conditions, with the best of instruments, can one observe details of angular size as small as 1 second of arc (1", equal to 1/3600 degree or 726 km at the center of the Sun's disk). The Solar Optical Telescope (see section devoted to it) will exceed this by a factor of 10-30, depending on the wavelength.

Secondly, sunlight at wavelengths shorter than those of the visible range is strongly absorbed by the Earth's atmosphere. Even though only about 1% of the Sun's total radiated energy is involved, these short wavelengths are intimately associated with hot regions and with particles accelerated to high energies. Thus some of the most significant solar features (e.g. "coronal holes"—see below) are clearly visible only from outside the atmosphere.

Four classes of solar features and phenomena are of particular interest to this 5-year plan:
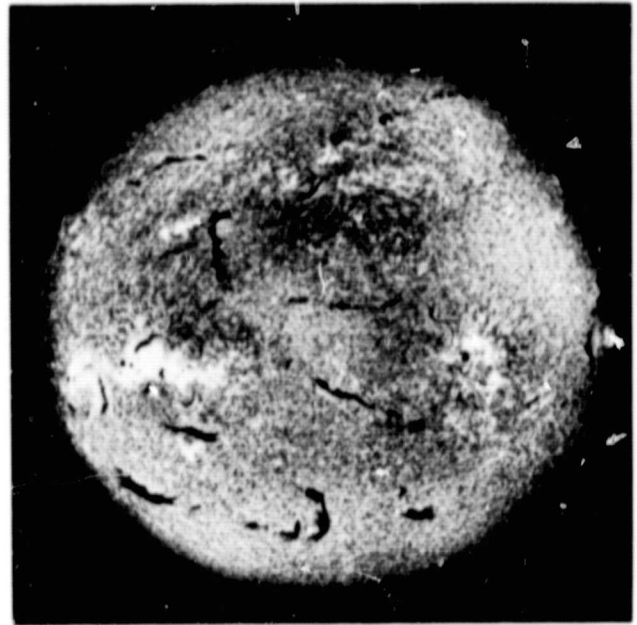

Fig. IV-3. Surface features of the Sun, viewed through a narrow spectral filter. The view includes two large centers of activity (bright) and several prominences (dark filaments).

1 Solar Convection

The visible surface of the Sun is in constant motion. Theory predicts that within 100,000 km of the Sun's surface, solar heat travelling outwards from the core is transmitted by convective flow (Figure IV-2). "Convection cells" representing such motions have indeed been observed on the solar surface—small shallow "granules", about 1000 km in diameter with lifetimes around 10 minutes, and larger "supergranules", $\approx$ 30,000 km across and lasting some 20 hours.

This constant motion appears to be associated with a rather unusual property of the Sun's atmosphere—namely, the fact that above the photosphere the local temperature increases rapidly with altitude: how can the extremely hot corona and chromosphere exist, if a cooler region separates them from the main source of the Sun's heat? It now seems that different modes of sound and magneto-hydro-dynamic (MHD) waves, rising from the turbulent photo-

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sphere, carry the necessary energy; some such waves have been observed and additional data about them are to be collected by the Solar Optical Telescope.

2 The Solar Magnetic Field

The Sun possesses a complex magnetic field, probably generated by large-scale convective flows and by the uneven rotation of the outer layers of the Sun, which move more rapidly near the equator and more slowly near the poles ("differential rotation").

The most conspicuous manifestation of this magnetic field are *sunspots*—darker regions of high magnetic intensity (1000-4000 gauss). When sunspots are viewed by appropriate instruments, it is seen that they are immersed in *active solar regions*, regions where the emission of selected spectral lines in the visible range and in the ultraviolet (UV), as well as X-rays emission, suggest the enhanced heating of the chromosphere and corona and the occasional acceleration of particles to high velocities. The most spectacular feature of such "solar activity" is the occurrence of *solar flares*, which are described separately below.

While sunspots constitute unusually intense regions of solar magnetism, widespread magnetic fields exist over the entire solar surface. They seem to be unevenly distributed and include intensely magnetized "magnetic knots", only about 1000 km wide, which contain an appreciable fraction of the total magnetic flux. Magnetic field lines often form large arches between regions of opposite magnetic polarity (Figure IV-4) and such arches appear to play an important role in the formation of cool dense clouds of plasma or "prominences".

Outside the closed loops of magnetic arches there exist "open" field lines, along which the Sun's magnetic influence extends to interplanetary space, to Earth and far beyond. When viewed from space in X-rays or extreme UV, such regions appear dark—hence the name "*coronal holes*"—and they seem to be the source of high-speed streams in the solar wind. The polar regions of the Sun represent large semi-permanent "holes" and one expects there a relatively fast flow of solar wind and a more orderly interplanetary magnetic field configuration, predictions which are to be examined on the Solar Polar Mission, scheduled for launch in 1983.
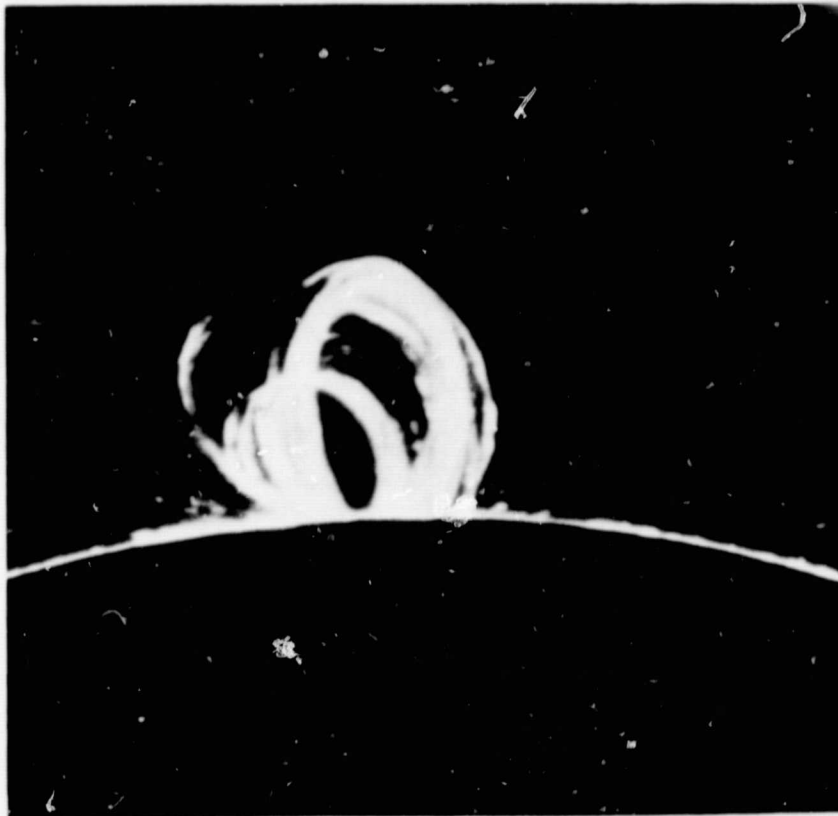

Fig. IV-4. Solar loop prominences (courtesy of Sacramento Peak Observatory).

3 Solar Activity

The frequency of sunspots and of all other manifestations of solar activity, such as solar flares, increases and declines over a cycle of about 11 years (the length of individual cycles may vary by a year or more). This cycle—discovered around 1843 but traced back through earlier records to about 1715—appears to be magnetic in nature: the Sun's overall magnetic poles seem to reverse their polarity every 11 years and the magnetic structure of typical sunspot groups also reverses polarity from one cycle to the following one.

The peak of each solar cycle, when sunspots and solar activity centers are most conspicuous, is accompanied by an increase in the "exotic" forms of solar energy reaching Earth—X-rays, solar flare particles and the energy of large geomagnetic disturbances. These heat up the uppermost part of the Earth's atmosphere—the thermosphere—from 600-800 K to about 2000 K (Figure IV-23), causing a general upward expansion of the atmosphere and hence, an increased resistance to the motion of near-Earth spacecraft. For example, the drastic downward revision in the expected lifetime of the Skylab orbiting laboratory, announced early in 1978, was due to an unexpectedly rapid rise in solar activity in the cycle following the solar minimum of 1975-6.

Many tentative correlations between the 11-year cycle and climate have been proposed. While most of these are still controversial (see section IV-d-4), there exists more definite evidence concerning links between climate and long-term averages of solar activity. It now seems (as suggested by Maunder and again by Eddy) that in the years 1645-1715 solar activity declined to a barely detectable level (Figure IV-5): this 70-year *"Maunder minimum"* seems to match a period of low auroral activity, unusually large differential rotation in the photosphere and cold climate on earth. Tree rings from that time also exhibit an increase in the concentration of radioactive carbon 14, suggesting that the cosmic ray intensity stayed at the higher-than-average level usually found during times of low solar activity. This last correlation has enabled scientists to extend their search for prolonged minima in solar activity to times when no regular observations of the Sun were made: several earlier long-term increases in C^{14} have been found which would signify earlier events similar to the "Maunder minimum", and they fit rather well with
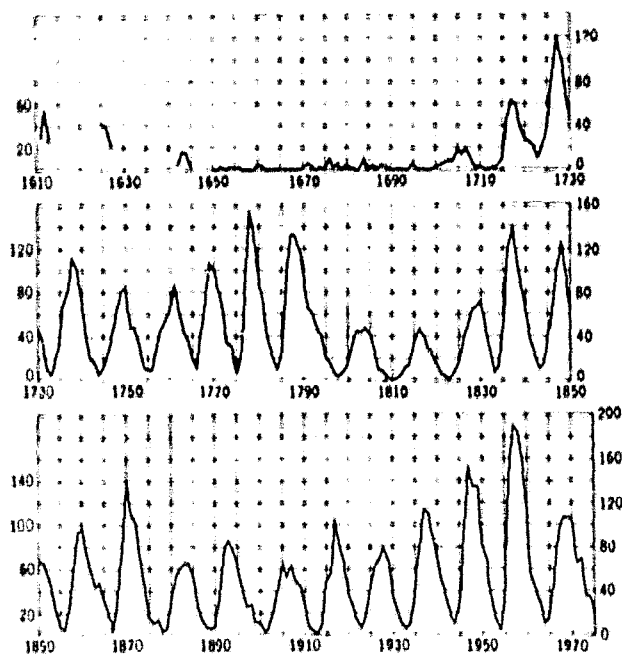

Fig. IV-5. The variation of mean annual sunspot numbers, extended back to 1611 by J. Eddy.

periods of unusually cold climate, deduced from historical records of winter severity and from the advance and retreat of Alpine glaciers (Figure IV-6).

4 Solar Flares

Among all phenomena associated with solar activity, the most rapid and spectacular is the *solar flare*, in which up to $3 \cdot 10^{25}$ joule ($\approx 10^7$ megaton TNT) may be released within 5-10 minutes. A considerable fraction of this energy (1/3 by one estimate) is channeled into the acceleration of particles to high energies.

The widespread occurrence of high-energy particles is perhaps the outstanding problem of modern astrophysics. On a galactic scale this problem involves the origin of cosmic rays and of extragalactic radio and X-ray emission. Inside our galaxy it is manifested by supernova remnants and pulsars, galactic X-ray sources and gamma ray bursts, by the radiation belts of the Earth and Jupiter and by other "non thermal" phenomena. Yet the acceleration process itself has only been observed in two cases—in solar flares and in the so-called "magnetospheric substorm", also to be studied as part of this 5-year plan (see further below). Observations on these two phenomena are complementary and jointly they offer the best hope for under-
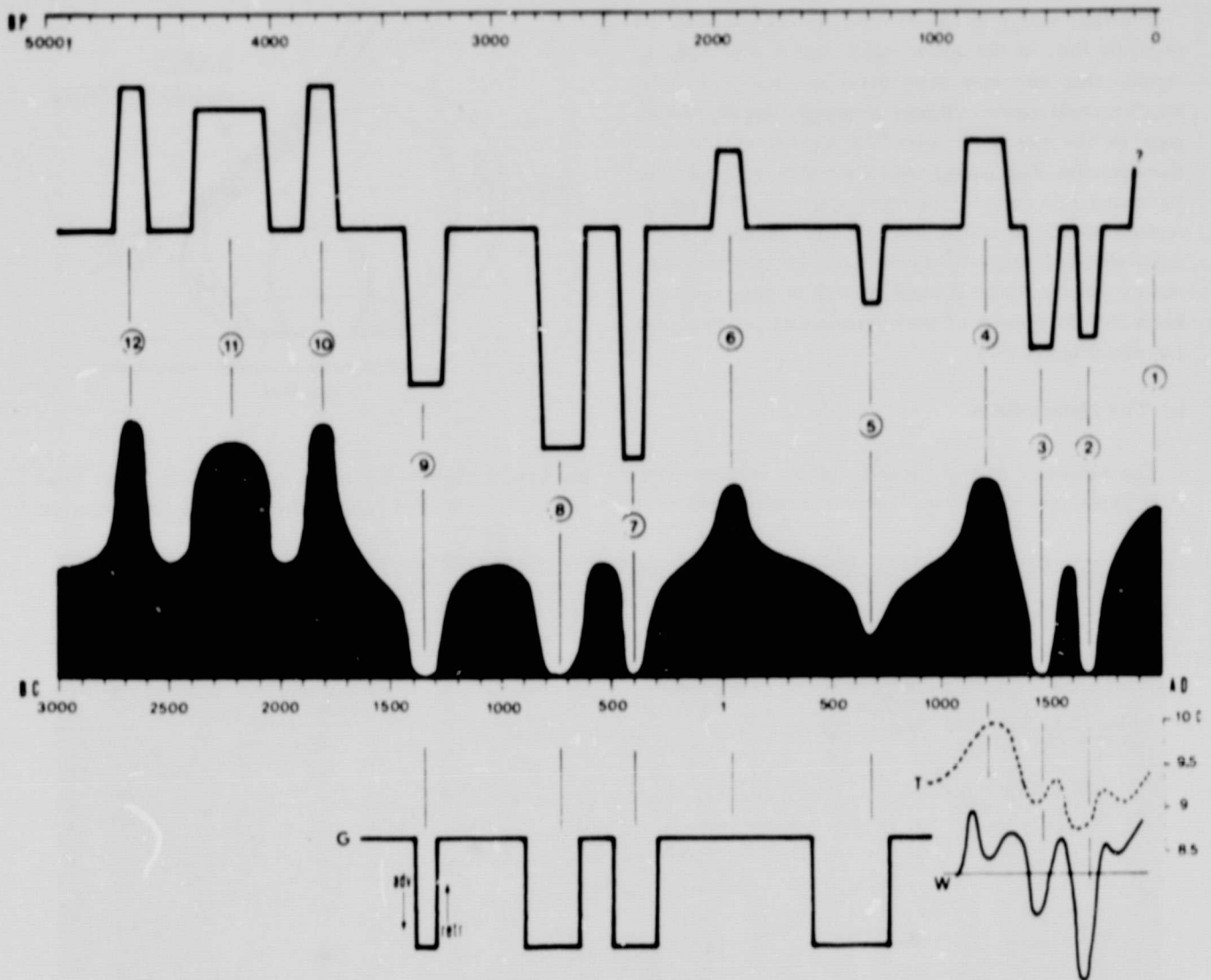
Fig. IV-6. The deviation of C^{14} production from an average trend (two top graphs — the black graph is a smoothed version of the histogram on top) compared to a historical record of winter severity (right hand bottom) and to the advance and retreat of Alpine glaciers (middle bottom). Compiled by J. Eddy.

standing a fundamental family of processes in our universe.

The flare is accompanied by a rapid brightening of spectral lines emitted from the chromosphere (Figure I-1), by UV and X-ray radiation, by certain structured radio emissions and by violent surges in the Sun's envelope. Energetic protons, heavier ions and electrons from solar flares have been observed by spacecraft instruments, and the X-ray emission from the flare region suggests that large numbers of electrons are accelerated there to energies of 10-100 keV during the initial "flash phase."

These emitted X-rays perturb the Earth's ionosphere and disturb the propagation of radio signals. Additional disturbances may occur later in the polar ionosphere ("polar cap black-outs"), when accelerated protons of 10-100 MeV (and sometimes even higher energies) reach the Earth's vicinity and are channeled by its magnetic field toward the geomagnetic poles.

The flare energy is almost certainly derived from the magnetic field of the active region and it is released so rapidly that one may view flares as "magnetic lightning"—a rapid release of magnetic energy somewhat analogous to the release of stored-up electric energy in a thunderstorm. This energy release is widely believed to be associated with forced "*magnetic merging*" (or "magnetic reconnection"), in which plasma flows containing oppositely directed magnetic fields converge into the same region, causing "mutual annihilation" of their magnetic fields and the transfer of their magnetic energy to plasma particles (Figure IV-7).
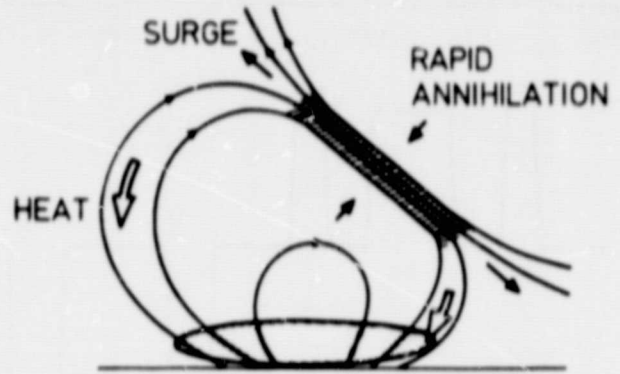
Fig. IV-7. Schematic model of magnetic merging during a solar flare.

b. The Heliosphere

The outermost part of the solar corona undergoes constant expansion, producing a continuous radial outflow of hot gas throughout the solar system. This is the *solar wind*, which at the Earth's distance (one "astronomical
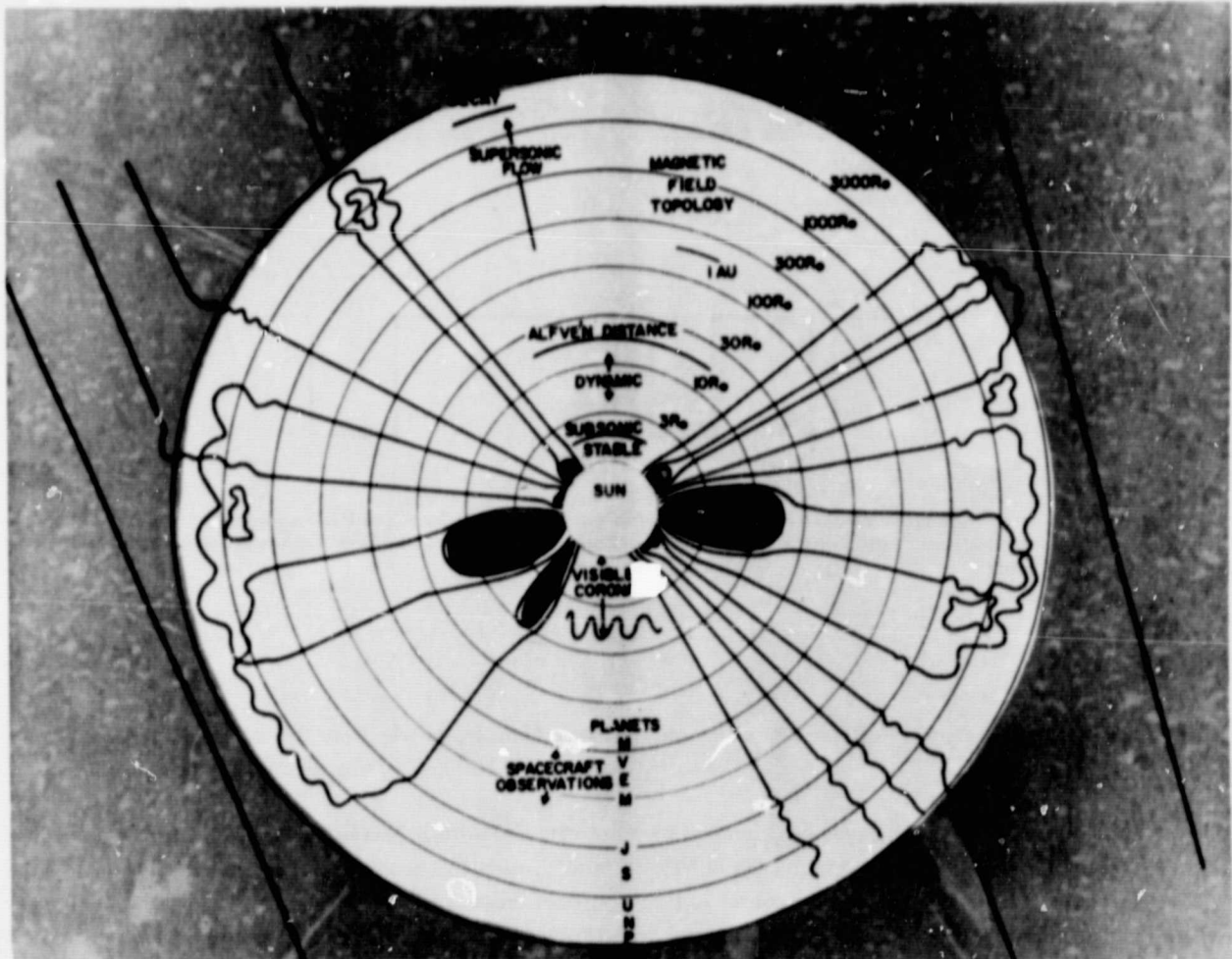
Fig. IV-8. Schematic view of interplanetary space near the orbital plane of the Earth, plotted in solar radii (1 AU ≈ 200 solar radii) on a logarithmic scale of distances. The spiral structure of magnetic field lines is omitted and the boundary of the heliosphere (light colored region) is arbitrarily set at 50 AU, although current observations extend only to about 8 AU (K. Schatten).

unit" or 1 AU) has a typical density of 5-10 ions/cm^3 and a velocity of 300-800 km/sec (Figure IV-10).

Fig. IV-9. Schematic view of a disk-like model of the interplanetary magnetic field (illustration provided by A. Hundhausen).

The solar wind dominates plasma processes throughout a large region around the Sun, the *heliosphere*, having an estimated radial extent of the order of 50 AU (Figure IV-8); note that distances from the Sun are drawn on an uneven scale!). Magnetic fields in the heliosphere originate on the Sun and are stretched out by the solar wind, becoming deformed into spirals as a consequence of the Sun's rotation (because of the uneven scale in Figure IV-8, this spiral deformation is omitted there). What lends the solar wind a particular importance to solar-terrestrial relations is that active phenomena in planetary magnetospheres—including the Earth's—derive their energy from the interaction between the solar wind and planetary magnetic fields.

As described in more detail in the next section, the Earth's magnetosphere presents the flow of the solar wind with an obstacle having a radius of about 25 earth radii ($1 R_E \approx 6370$ km). Up to about 0.1% of the solar wind energy flux incident on this cross section, some $10^{11} - 10^{12}$ watts, are absorbed by the magnetosphere and drive the various plasma processes observed there: a considerable fraction of this energy ends up being dissipated in the upper polar atmosphere when auroral particles are precipi-

tated and electric currents are driven through the ionosphere.

The *interplanetary magnetic field*, embedded in the solar wind, may in general point either "toward" the Sun or "away" from it, reflecting the magnetic polarity of the region which would be reached if its field lines were followed all the way to their source of the Sun. During any solar rotation period, two, four or even more such "sectors" of opposing interplanetary fields may be observed in the Earth's neighborhood, and some intriguing correlations between weather patterns and the time of passage of boundaries between such sectors have been published. Since 1976, when Pioneer 11 observations indicated that the interplanetary magnetic field may be disk-like (Figure IV-9), it has been suggested that sectors represent undulations in the mid-plane of this disk: the forthcoming Solar Polar Mission is expected to furnish additional information about this point.
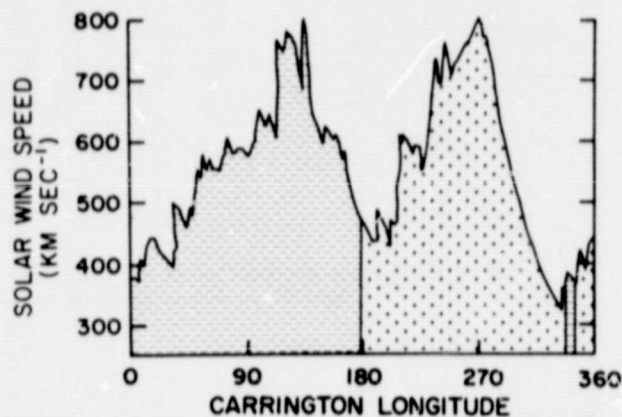
Fig. IV-10. The velocity of the solar wind as observed during one full solar rotation in 1974, plotted against the inferred longitude of the source region in the Sun's corona. Two fast streams are observed, associated with sectors of opposite polarity (+ shading indicates magnetic field lines pointing away from the Sun). In this particular case it was shown that the two streams probably arose from observed equatorward extensions of the southern and northern polar "coronal holes", respectively, which possessed the appropriate magnetic polarities (A. Hundhausen).

The velocity of the solar wind varies. *Fast streams* (two of which are shown in Figure IV-10) apparently originate in "coronal holes" and are responsible for moderate magnetic disturbances observed on Earth with a 27-day recurrence. Such streams may be characteristic of the region above the Sun's magnetic poles, since large "holes" are permanently located around the poles of the Sun; the Solar Polar Mission will study this region for the first

time. A general theoretical explanation for the expansion of the solar wind does exist, but not all observed details have been satisfactorily explained; some such details depend on the magnetic structure of the regions from which the solar wind originates, their temperatures and heat flows, information which the Solar Probe mission (described in a later section) will try to obtain. Studies of the composition of the solar wind—performed by indirect means in the past, and scheduled to be carried out directly with the mass spectrometers of ISEE-3 and IPL—can also provide valuable information about the source regions of the solar wind, especially if atoms ionized by different amounts can be distinguished and identified.

Finally, not only does the solar wind carry extensive information relevant to the Sun's corona and to solar-terrestrial relationships, but it also exhibits many interesting *plasma processes* which can be observed in-situ—shocks, discontinuities, small-scale irregularities and populations of energetic particles, some of which may be produced by collisionless heating in interplanetary shock waves. Related to these processes are interplanetary magnetic irregularities, which exist in many different types and sizes; such irregularities can scatter cosmic ray particles, which are observed to be modulated in the heliosphere in several different ways, and also strongly affect the propagation of energetic particles from solar flares.
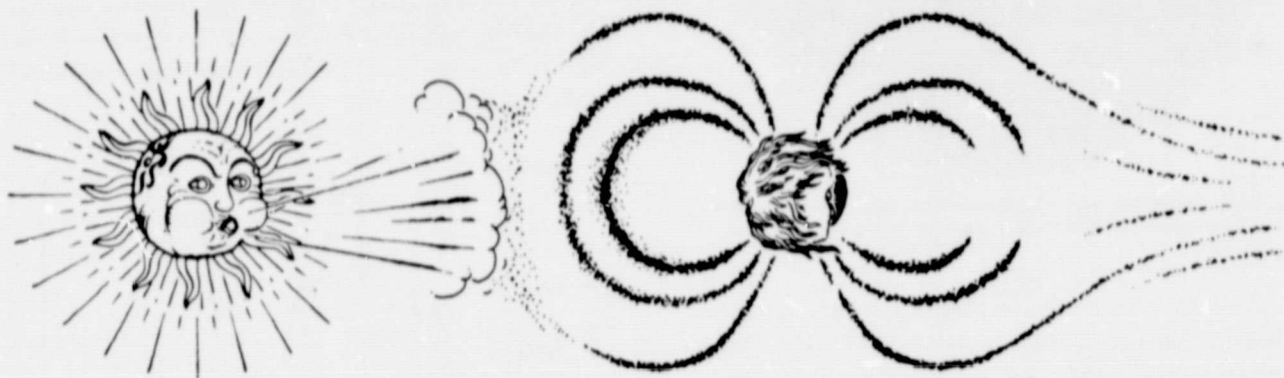

Fig. IV-11. A somewhat simplified view of the interaction between the solar wind and the Earth's magnetosphere (from the announcement of the advanced summer institute of reference 23-3).

c. The Earth's Magnetosphere

We are fortunate to live on a magnetic planet: the geomagnetic field, originating deep in the Earth's core, constitutes an obstacle to the solar wind, deflecting it and creating a cavity to which the solar wind does not have direct access. This cavity, together with its boundary regions, is known as the Earth's *magnetosphere*.

The importance of the magnetosphere to solar terrestrial science stems from two distinct sources:

First, the magnetosphere *provides the link* between the solar wind and the upper atmosphere, a link which must be understood in order to explain observed correlations between the two—e.g., the relation between interplanetary sector boundaries and the frequency of mid-latitude storms in the lower atmosphere (sect. IV-d-4).

Some of our knowledge about this linkage is described below. In particular, it appears that the magnetosphere:

i. Receives energy from the solar wind through *electric fields* which propagate along "open" field lines;

ii. "Captures" some of the hot solar wind plasma in the *cusp and mantle* regions (Figure IV–12); and

iii. Produces earthward flows of energetic particles in recurrent sequences of stretching and rebounding of the geomagnetic tail, known as *magnetospheric substorms*.

At the other end of this linkage, the magnetosphere affects the upper atmosphere by driving large-scale electric currents through the ionosphere, currents which not only deposit energy but also exert a force. In addition, energy
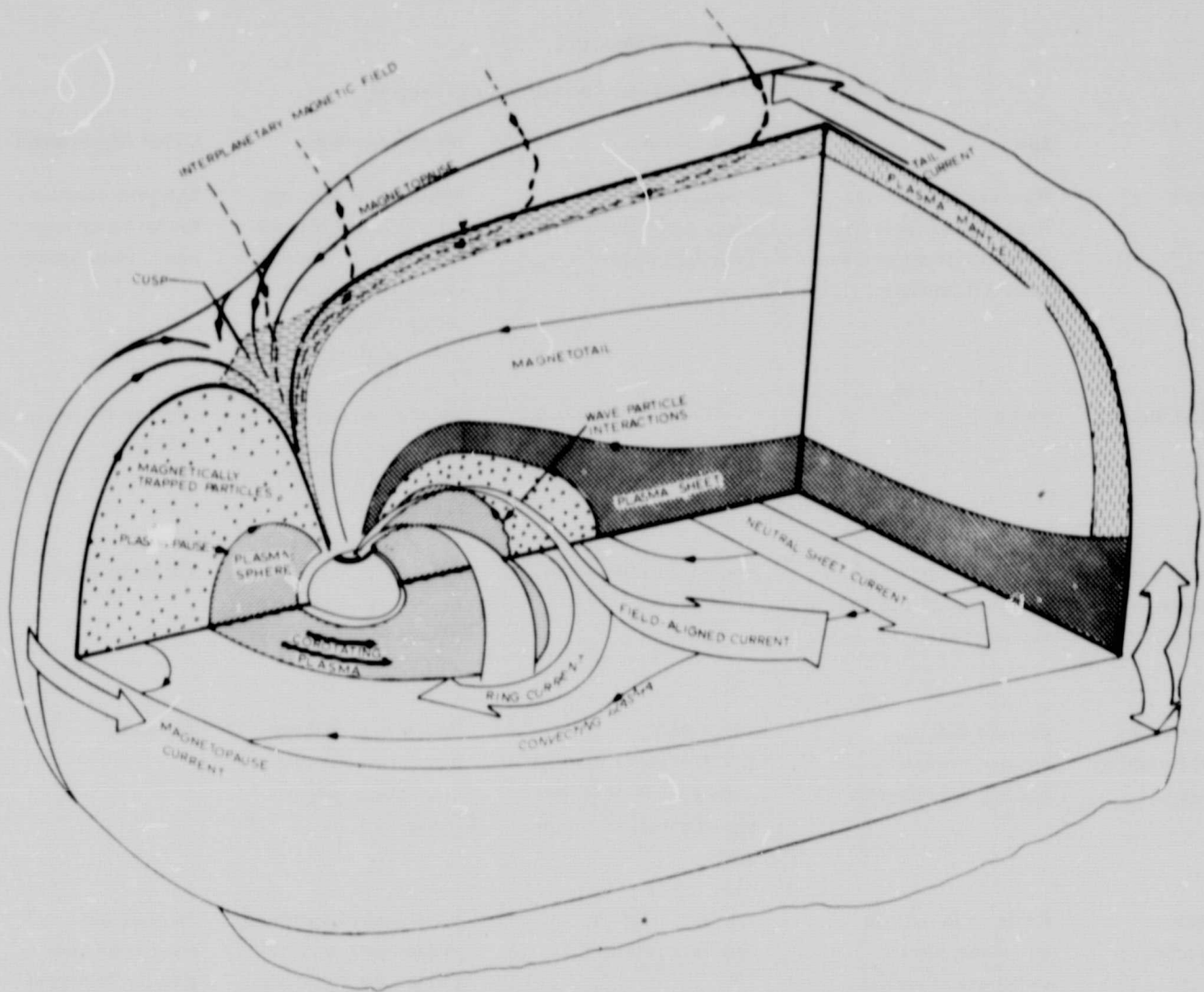
Fig. IV-12. Schematic view of the Earth's magnetosphere (from reference 32-2).

is deposited when accelerated electrons precipitate into the atmosphere in the *polar aurora* (Figure I-3). Accelerated protons and ions may also end up in the atmosphere, although other mechanisms may contribute to their loss as well.

Secondly, the magnetosphere is our *most accessible "cosmic plasma"*. Rarefied plasmas, permeated by large-scale magnetic fields, determine much of the behavior of the Sun's envelope and of the heliosphere, and yet it is in the Earth's magnetosphere that the processes involving them are most readily observed and studied (Table IV-1).

Such "cosmic plasmas" also dominate the magnetosphere of Jupiter and other planetary magnetospheres, pulsar magnetospheres, supernova remnants such as the

Crab nebula, our galaxy itself and extragalactic sources of radio waves and X-rays. But only in the Earth's magnetosphere are the relevant plasma processes accessible to in-situ measurements—and with the Spacelab facilities, perhaps also to in-situ active experimentation. It is here, therefore, that the information needed for the understanding of more distant phenomena is often most clearly revealed.

Consider for example *particle acceleration to high energies,* a process fundamental to solar flares and to many additional "cosmic" phenomena (sect. IV-a-4). The terrestrial counterpart to flares are magnetospheric substorms; both phenomena are believed to derive their energy from the rapid "annihilation" of magnetic fields, but whereas no flare associated changes in the solar magnetic field have

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Table IV-1

Plasma Physics in the Solar-Terrestrial Environment

	Sun	Heliosphere	Magnetosphere	Upper Atmosphere
Waves	Waves heating corona. Radio bursts from flares. Surface waves (Moreton waves) from flares.	Propagating disturbances. Solitary waves. Type III bursts.	Whistlers; Kilometric radiation; micropulsations; $n + \frac{1}{2}$ harmonic electrostatic waves; ion cyclotron waves; power grid harmonics.	Sub-protonospheric mode; active experiments from Spacelab.
Instabilities	Flares	"Turbulence" producing local inhomogeneities	Substorms, flapping of magnetopause; Wave-particle interactions.	"Spread F" rising bubbles.
Sources of Energetic Particles	Flares, activity centers; the corona as a source of the solar wind.	Shocks; interplanetary acceleration.	Substorms; $E_{\parallel}$ · heating in bow shock; source of plasma sheet; neutron albedo.	The polar wind
Boundaries and Boundary Layers	Current sheets in coronal streamers; coronal hole boundaries.	Tangential discontinuities; D-sheets and other structures; shocks; interplanetary sector boundaries	Bow shock; Magnetopause; mantle, cusp boundaries; plasmapause	"Troughs"
Electric currents	Currents in coronal streamers; electrodynamics of active regions	Currents in sheets and discontinuities	Field aligned currents; magnetopause current; plasma sheet current.	Auroral and equatorial electrojets; S_q "dynamo current" in the ionosphere.

been confirmed, the characteristic magnetic variation during substorms—in particular, the "snapping back" of the distended tail—has been repeatedly observed by satellites.

Such satellites have also observed at least 3 distinct acceleration mechanisms:

i. Acceleration by large-scale electric fields (such as those of Figure IV-13) which drive particles earthward—either steady fields entering the magnetosphere from the solar wind along "open" field lines (see below), or short lived but intense fields induced when the tail's field lines snap back during substorms.

ii. Rapid acceleration of ionospheric electrons and ions by voltage drops along magnetic field lines.

iii. Rapid impulsive acceleration of plasma sheet particles in intense substorms, possibly associated with "magnetic merging" there (Figure V-1 and text below).

Nowhere else in the universe—except for research accelerators used by scientists on the ground—can the acceleration of particles be as well understood and as thoroughly observed as it can in the Earth's magnetosphere.

The Earth's magnetosphere begins at a rather abrupt boundary, the *magnetopause*: as Figure IV-12 shows, the dayside magnetopause is compressed by the impact of the solar wind, to a distance of about 10 R_E (Earth radii). On the night side (Figures IV-12 and V-1) the magnetosphere is drawn out into a long *tail*, reaching beyond the orbit of the moon ($\approx$ 60 R_E) and having a radius of about 25 R_E. The manner in which the tail ultimately ends is not known, and this point is to be explored by the Geomagnetic Tail Laboratory, one of the components of the OPEN mission. About 3 R_E upstream from the dayside magnetopause there exists a collision-free bow shock, in which the impinging solar wind is slowed down and heated: the region behind this shock, containing modified solar wind plasma, is known as the *magnetosheath*.

Close to Earth the field resembles a *dipole*, a structure with two magnetic poles (like a bar magnet). Thus there exist on the magnetopause two points (one in each hemisphere) where magnetic field lines closing on the front of the Earth become separated from those swept to the rear, and near these points one finds regions of weak magnetic field, defining the so-called *polar cusps* (Figure IV-12). The cusps are the "weak points" in the Earth's magnetic boundary and magnetosheath plasma is able to breach them, some of it flowing deep into the magnetosphere along magnetic field lines and some of it expanding into a "plasma mantle" alongside the tail.

What may be even more significant, in or near the cusps the process of *magnetic merging* (or "magnetic reconnection") apparently takes place, establishing a connection between interplanetary magnetic field lines and those emanating from the neighborhoods of the Earth's magnetic poles ("polar caps"). Such "open" field lines are believed to couple the solar wind and solar energetic particles to the magnetosphere and to transmit from the solar wind the energy and the electric field which drive magnetospheric phenomena.

Across the middle of the tail there exists a thick layer of hot plasma, the plasma sheet (Figure IV-12). The origin and dynamics of the plasma sheet are still imperfectly understood, but the region appears to be the site of the primary release of energy in *magnetospheric substorms*, rapid events which resemble solar flares in many ways. The impulsive phase of a substorm may last 10–45 minutes (possibly less) and when it is over, the tail's magnetic field is found to be less distended than before, indicating that part of its energy has been converted to other forms.
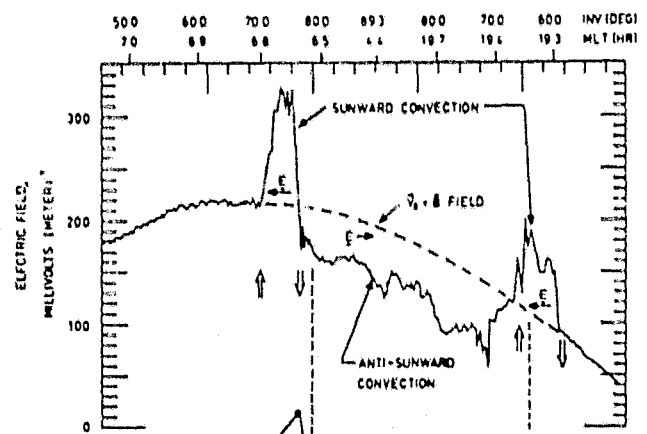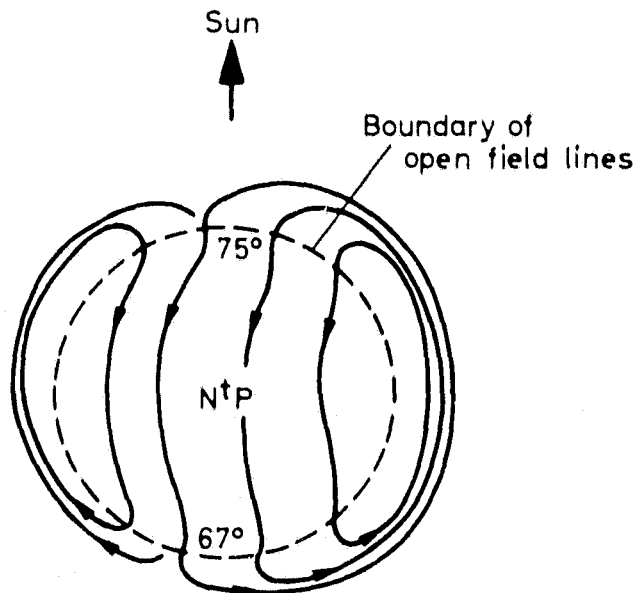
Fig. IV-13. (Right side) Electric fields observed by the Injun 5 satellite as it passed above the magnetic pole in an orbit approximately perpendicular to the Earth-Sun direction, across the center of the pattern depicted on the left side. The average trend (broken line) is contributed by the orbital motion of the spacecraft, while deviations from it measure the electric field intensity. (Left side) Contours of constant electrical potential in the polar ionosphere, derived from observations such as the one on the right. The broken line depicts the boundary of "open" magnetic field lines, merged with the interplanetary magnetic field, which transmit the electric field to Earth: the field direction in the right-hand panel reverses when this line is crossed. The total voltage drop across the pattern typically varies from 20,000 to 80,000 volt.

The collapse of the tail field during a substorm appears to be associated with a strong induced electric field which drives large numbers of plasma sheet particles earthward, imparting to them considerable additional energy in the process. Electrons energized in this manner may be precipitated into the upper atmosphere, producing there brilliant auroral displays (Figure I-3) which peak in the "auroral oval" between magnetic latitudes of 65° and 70°. Protons, on the other hand, may find themselves injected into the trapped population of the *ring current* and *radiation belt*. Substorm activity typically occurs at intervals of several hours and is most intense when the interplanetary magnetic field has a southward component, a condition which aids the merging of interplanetary field lines with those of the Earth. When large numbers of particles are injected into the ring current (e.g. in a sequence of intense substorms, initiated by some interplanetary disturbance), the result is a profound global disturbance of the magnetic field observed on the ground, known as a "magnetic storm."

Substorms are accompanied by a complex array of linked phenomena, about which much remains to be learned. Secondary electric fields produced by the earthward flow of plasma sheet particles lead to "*parallel electric fields*" ($E_\parallel$), i.e. voltage drops along magnetic field lines: because charged particles are guided along magnetic field lines, such voltage drops can accelerate them quickly and efficiently. Beams of ionospheric oxygen ions, accelerated upward by these electric fields and contributing to the ion population of the ring current, have been observed (Figure IV-14), and many auroras and particle flows in space also appear to be caused by $E_\parallel$. Accelerated beams of electrons are apparently unstable and dissipate part of their energy in the form of intense "*kilometric radiation*" (i.e. having wavelengths of the order of 1 km, similar to radio waves of the standard A.M. broadcast band), studied from spacecraft since 1971. Intense flows of particles with energies 10-15 times larger than those typical of the aurora have also been observed in the tail ($\approx 35\ R_E$) during substorms, and may be the terrestrial counterpart of high-energy protons produced in solar flares.

Closer to earth a relatively stable region of trapped radiation exists, containing particles from the ring current which have gradually undergone additional acceleration, and also high-energy protons which are a secondary product of cosmic ray interactions with the atmosphere. A trapped population of cold ions which form an extension
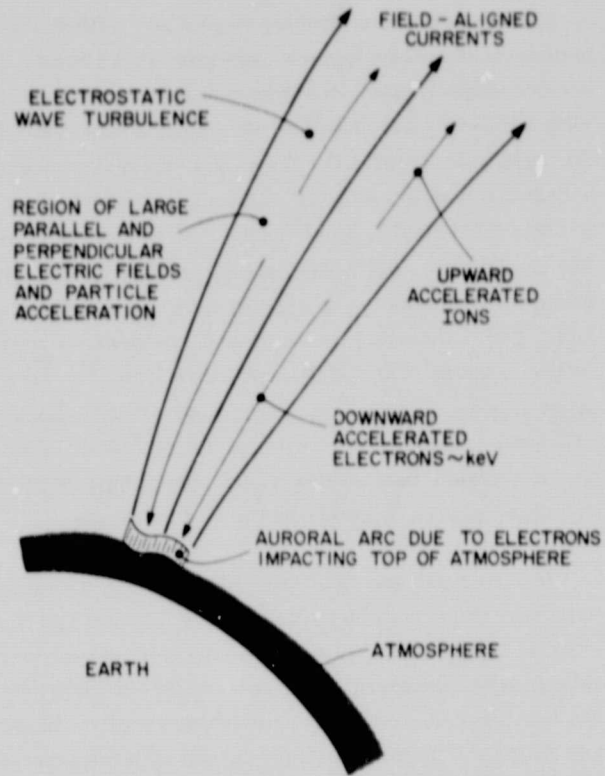
Fig. IV-14. Schematic view of voltage drops along magnetic field lines, accelerating electrons downwards into the atmosphere and positive ions upwards into the right current (from reference 11-3).

of the ionosphere and which tend to corotate with the earth—the "*plasmasphere*" in Figure IV-12—occupies a wide region around the earth, and is contained by magnetic field lines which extend to distances of up to 3-6 R_E. Interesting modes of plasma waves are created by interactions between this cold plasma and the hot particles of the ring current (or those of the substorm), and such waves may cause the latter to be precipitated into the atmosphere. The AMPS program (see appropriate section) plans to initiate such precipitation artifically, using Spacelab to inject electromagnetic signals and cold lithium ions into the magnetosphere.

Large-scale electric fields, which may originate on "open" field lines (Figure IV-13) appear to permeate much of the magnetosphere and produce a widespread "convective flow" of plasma, from the tail towards the dayside (this flow has the same general direction as the flow produced by substorms but is much weaker, and it seems to exist at all times). Likewise, there exists at all times a complex system of electric currents flowing along

magnetic field lines into the ionosphere and out of it (Figure IV-15), approximately along the boundaries of the auroral oval. Both the fields and the currents increase in strength during substorms, and the currents in particular may provide an important input of energy into the polar ionosphere.

ELECTRIC CURRENTS FROM THE MAGNETOSPHERE COUPLE TO THE ATMOSPHERE

ESCAPING IONS

ELECTRIC CURRENTS

KILOMETRIC RADIATION

AURORAL ZONE
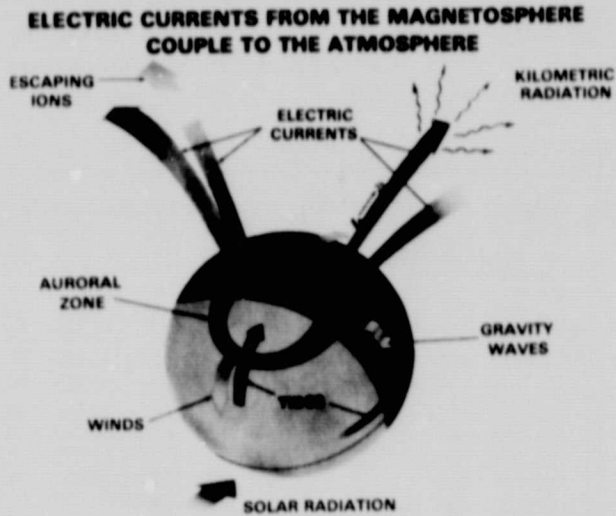
GRAVITY WAVES

WINDS

SOLAR RADIATION

Fig. IV-15. Electric currents flowing into the auroral oval and out of it, together with some associated phenomena.

The Colgate committee (sect. III-c and ref. 11-3) has recognized the unique role of the Earth's magnetosphere as a "laboratory for cosmic plasma physics" and has identified 4 critical problem areas in magnetospheric physics (Figure IV-16):

i. How does the solar wind transmit energy to the magnetosphere?

ii. How does solar wind plasma enter the magnetosphere?

iii. How does the geomagnetic tail dissipate stored energy to create substorms?

iv. How are the atmosphere, ionosphere and magnetosphere coupled to each other?

Some clues, theories and correlations now exist which can lead us towards answering each of these questions. However, many additional observations are needed—in particular, simultaneous correlated observations at several points—and the most important among these are included in the missions proposed by this 5-year plan.

PROBLEM #1.
HOW DOES SOLAR WIND COUPLE ENERGY TO MAGNETOSPHERE?

PROBLEM #2.
HOW DOES SOLAR WIND COUPLE PLASMA TO MAGNETOSPHERE?

PROBLEM #3.
HOW DOES TAIL DISSIPATE STORED MAGNETIC ENERGY TO CREATE SUBSTORMS?

PROBLEM #4.
HOW DOES MAGNETOSPHERE COUPLE WITH ATMOSPHERE AND IONOSPHERE?

plasma sheet   magnetopause

solar wind

Moon

reconnection ?
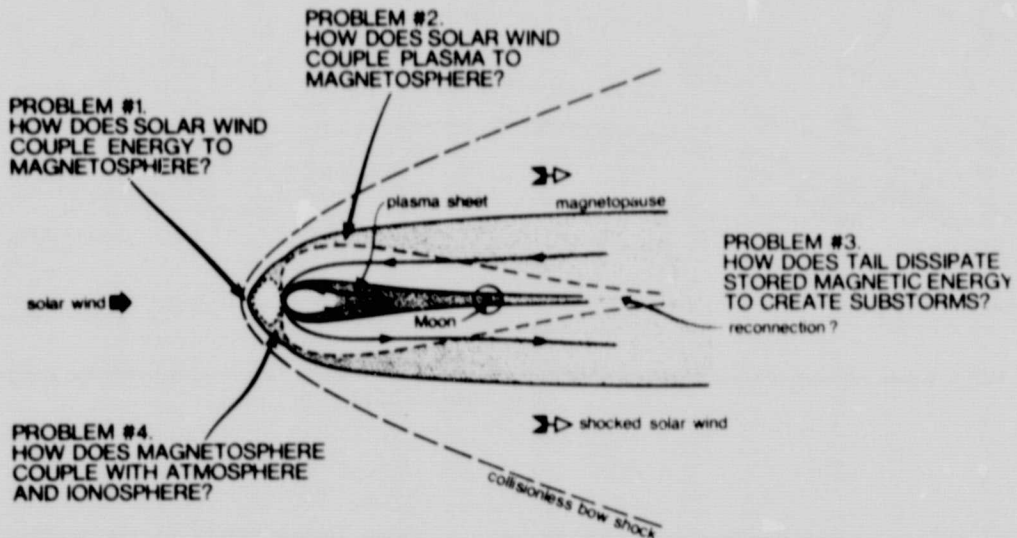
shocked solar wind

collisionless bow shock

Fig. IV-16. Some outstanding problems of magnetospheric physics (reference 11-3).

d. The Upper Atmosphere

1 The Stratosphere and Mesosphere

Almost all human activities take place in the *troposphere*, the atmospheric layer adjacent to the ground (Figure IV-17). The troposphere exhibits complex dynamics—"weather" in everyday language—since its main heat source is at its bottom, where sunlight heats the ground and the ocean surface. Because heat energy is supplied from below and temperatures drop with increasing altitude, a situation is established which encourages the development of large scale convective flows—including thunderstorms, hurricanes and other familiar forms.

Between the altitudes of 13 ± 5 km ("tropopause") and 50 ± 5 km ("stratopause") this drop in temperature ceases and even reverses (Figure IV-18) due to the presence of a small but significant proportion of *ozone* (O_3); ozone strongly absorbs solar ultraviolet radiation below 3000 A, a range which contains about 1% of all the solar energy incident on Earth. This region is termed the *stratosphere* and the reversed temperature profile in it has a strong stabilizing influence; in the next higher layer, the *mesosphere* (50 ± 5 to 80 ⁺ 5 km), the temperature once again decreases with altitude.

The combined stratosphere-mesosphere system, sometimes called the *middle atmosphere*, is thus also "heated
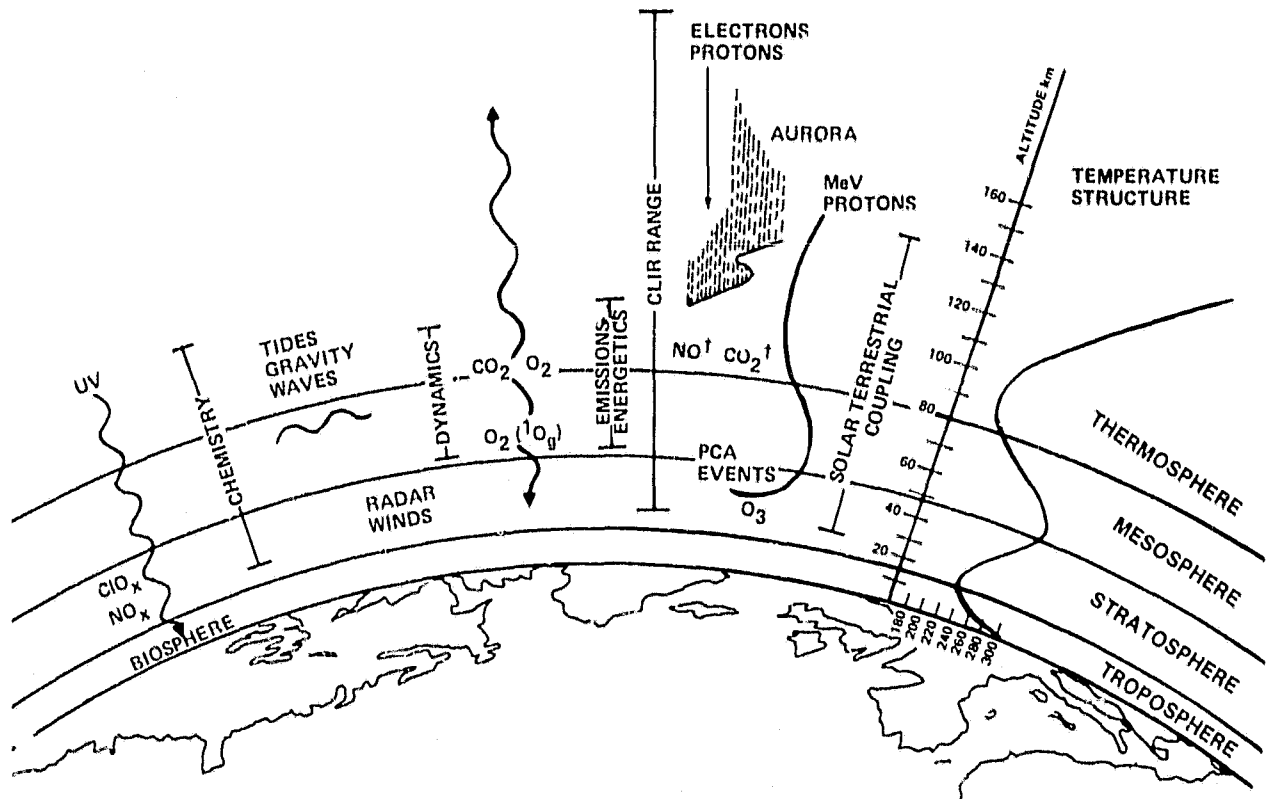
Fig. IV-17. Schematic view of the atmosphere with its active minor constituents, temperature profile and energy transfer process (from reference 35-5).

from below" and can generate its own flows (many define the "middle atmosphere" as also including the lower thermosphere—see IV-d-2). However, observations of its dynamics have been scarce, because the region is not easily accessible to in-situ observations.

When the dynamics of the middle atmosphere are examined more closely, they are found to depend critically on a complex web of linked chemical reactions, between constituents which form only a tiny fraction of the total atmospheric mass. As was already noted,

Fig. IV-18. The nomenclature of atmospheric layers and boundaries, together with the atmospheric temperature profile (altitudes and temperatures may vary with location and time: see text).

ozone—a minor constituent comprising 1-10 parts per million of the stratospheric gas—contributes the bulk of the heating, while CO_2, O_3 and H_2O (water vapor) dissipate

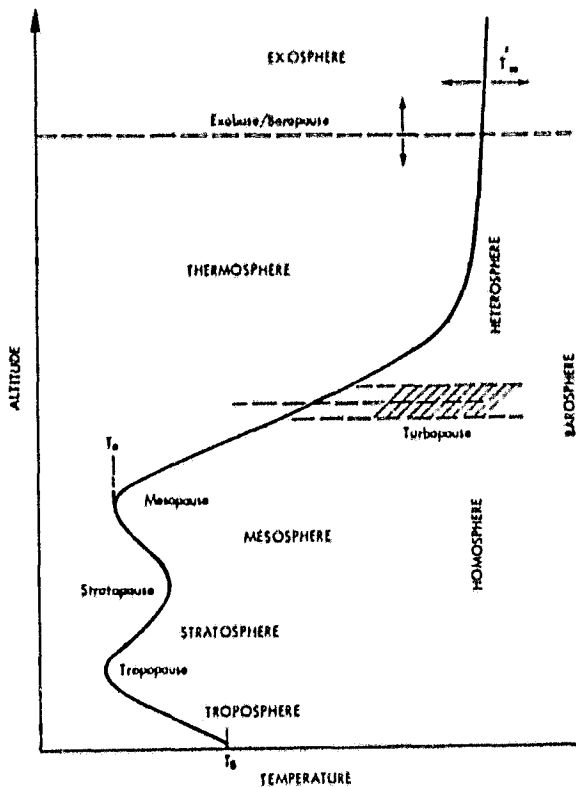most of the heat by infra red (IR) emission (Figure IV-19). Water vapor is in equilibrium with the reactive compounds H_2O_2, OH and HO_2, while "odd nitrogen" compounds such as NO and NO_2 (collectively denoted "NO_x") limit the amount of O_3 by interacting with it. To complete the description of this "chemical soup" (see Figure IV-20) one must also take into account chlorine compounds, many of which appear to have a man-made origin
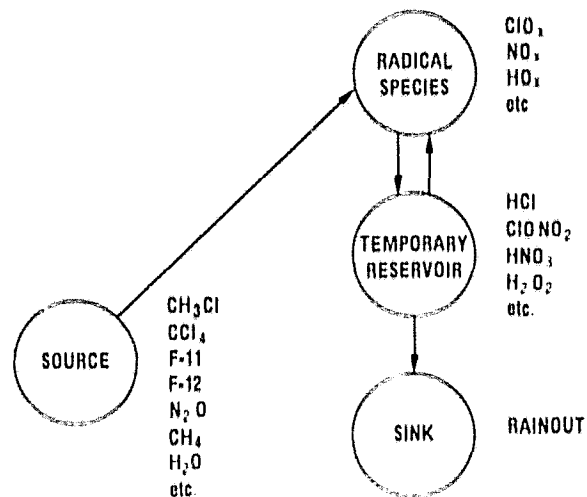
Fig. IV-20. Schematic of the stratospheric chemical system (R. Stolarski).
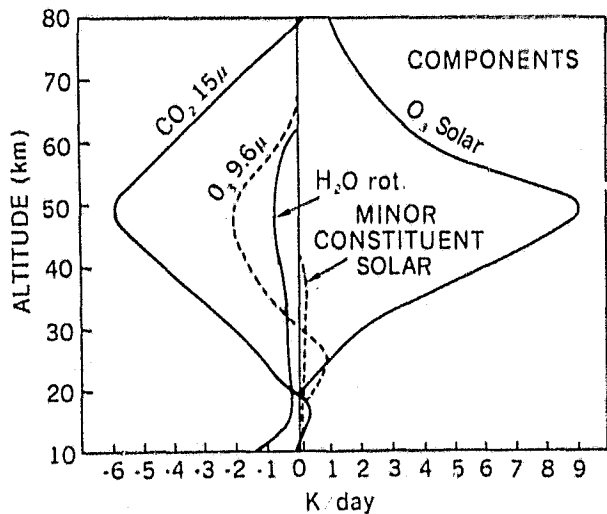

Fig. IV-19. The rate of heating and cooling (in degrees Kelvin per day) produced by the major absorption and emission processes of radiation in the middle atmosphere (after reference 25-9).

(see below) and sulfur, which contributes to stratospheric aerosols. Furthermore, chemical equilibrium conditions vary with altitude—O_3, for instance, is mostly produced near the top of the stratosphere, but its highest concentrations are found in its lower levels (Figure IV-21).

Such a complex interacting mixture may well undergo significant changes if some critical ingredient in it is perturbed, and special concern has been voiced about possible *man-made perturbations affecting ozone*, which shields living organisms from potentially harmful solar UV radiation. An increase of NO_x, for instance, increases the rate at which O_3 is destroyed: the temporary decrease of the O_3 content above 35 km by about 15%, following the arrival in polar regions of protons from the big flare of

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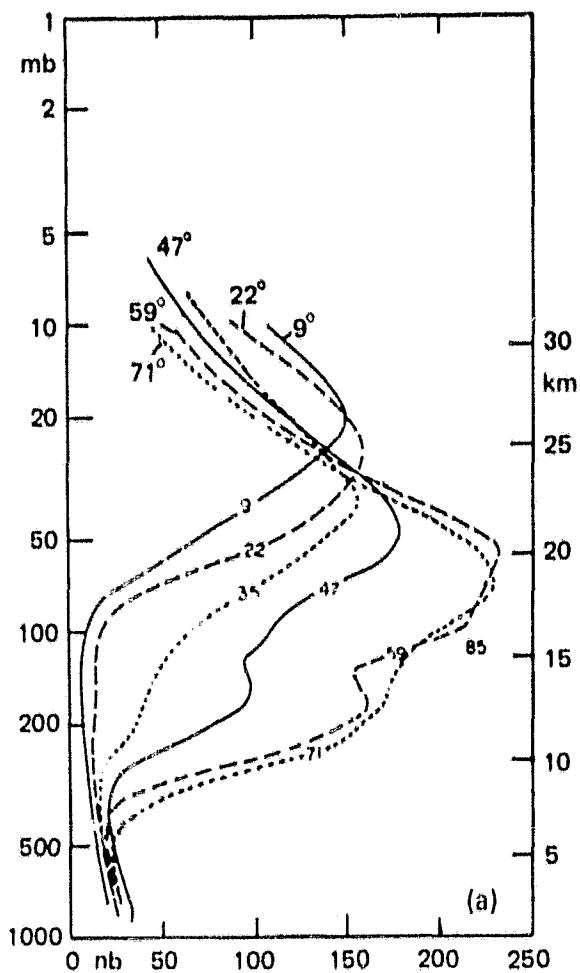
Fig. IV-21. Density profiles of atmospheric ozone, observed during spring with the help of balloons (Dütsch, 1971). Each curve is tagged by the appropriate geographic latitude; divisions at the bottom and on the left give ozone partial pressure and atmospheric total pressure, respectively, in units differing by a factor of 10^6.

which then proceeds to destroy O_3 catalytically with great efficiency.

TOTAL OZONE ABOVE 4 MB ($\sim$35 km) MEASURED WITH NIMBUS BEFORE AND AFTER SOLAR PROTON EVENT

Fig. IV-22. A sharp drop in ozone content of the upper strato-sphere, following the arrival of solar flare protons in polar regions and observed from Nimbus 4. The vertical scale gives the height in units of 0.001 cm of a column of ozone at sea level pressure, containing as much ozone as a column of the same cross-section above the 4 millibar pressure level, at the observation point (D. Heath).

During the coming decade a great amount of new information about the middle atmosphere will be provided by remote sensing from space—through measurement of IR emission and absorption by atmospheric molecules and radicals, and through probing of the atmosphere by lidar. Such techniques are further described in the sections of this plan concerned with SME, UARS, Lidar and CLIR (see table of contents). Data obtained from these missions will ultimately be entered into large-scale computer models simulating the behavior of the middle atmosphere; initial versions of such models already exist. An extensive international collaborative study of the middle atmosphere, the Middle Atmosphere Program (MAP), is scheduled for 1980-1985.

August 1972 (Figure IV-22), was probably caused by enhanced production of NO$_X$.

The possibility that nitrogen compounds from artificial fertilizers or from the exhausts of supersonic transport air-planes in the lower stratosphere can have similar effects has been studied, but the largest concern at present is over the effect of man-made chlorine compounds $CFCl_3$ and CF_2Cl_2 ("Freon 11" and "Freon 12"), which are widely used in refrigeration and in aerosol spray cans. These com-pounds are extremely stable and can be expected to reside in the troposphere for decades until they diffuse into the upper atmosphere, where solar UV radiation decomposes them. Such decomposition, however, liberates chlorine,

2 The Thermosphere and Exosphere

Above the boundary of the mesosphere (the "meso-pause" at 80 ± 5 km) the atmosphere is heated up once more, this time by the absorption of solar X-rays and of solar UV at wavelengths below 1800 A. Since the inten-sity of such radiation varies greatly over the solar cycle,

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the temperature of this layer, the *thermosphere*, also varies from $\approx$ 600-800 K at solar minimum to $\approx$ 2000 K at times of high solar activity (Figure IV-23). Above about 400 km collisions between atmospheric particles become rather rare, and the part of the atmosphere which lies beyond this altitude is known as the *exosphere*.

The lower thermosphere contains several noteworthy features. At 110 ± 10 km one finds the *turbopause*, the transition between a well-mixed atmosphere of approxi-

Fig. IV-24. The cloud of neutral atomic hydrogen surrounding Earth, viewed from the lunar surface in the 1216 A Lyman-alpha spectral line of hydrogen. This picture was taken by Apollo astronauts on 21 April 1972, using the Naval Research Laboratory's Far UV Camera (picture courtesy of G. Carruthers).
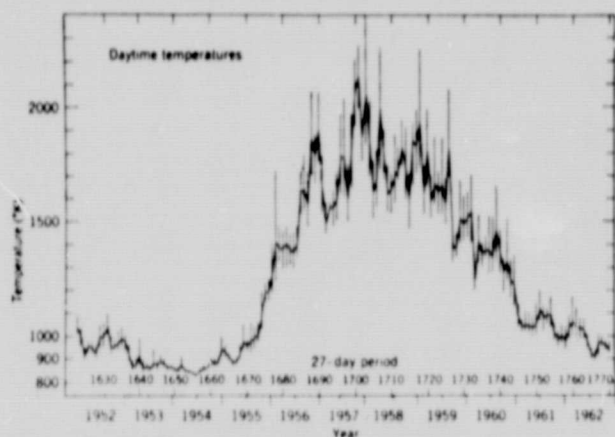

Fig. IV-23. Variation of thermospheric temperatures over a solar cycle (after M. Nicolet).

mately uniform composition and one in which the abundance of each constituent decreases with altitude at its own rate. The lightest constituents decrease most slowly, so that atomic oxygen (O) soon overtakes N_2 as the major atmospheric constituent, while beyond about 1000 km hydrogen is the main remaining gas. The hydrogen surrounds the Earth in a cloud which extends to great distances (Figure IV-24) and charge exchange with its atoms seems to be an important loss mechanism for ring current particles injected during substorms. As has already been noted, the heating of the thermosphere at times of high solar activity causes it to expand upwards and appreciably increases the atmospheric resistance encountered by near-earth satellites.

The lower thermosphere also contains a layer of Na and K around the altitude of 80-90 km, and Mg (neutral

and ionized) has been observed at and above this level: these particles probably originate in meteorites. Such atoms and ions may be detected by lidar (see appropriate section) and they may aid the study of gravity waves, which are believed to propagate near the mesopause.

3 The Ionosphere

At the higher altitudes of the thermosphere an increasingly large fraction of the gas is ionized: this region is called the *ionosphere* (it overlaps the thermosphere, but when the term "ionosphere" is used the emphasis is placed on the ionized components). The ion density rises to a maximum of $\approx 10^6$ per cm^3 at $\approx$ 300 km (Figure IV-25) and decreases rather slowly afterwards, reaching about 10^4 cm^{-3} at 1000 km. At still larger distances the ion density is stratified not according to altitude but according to distance along magnetic field lines, which control the motion of the ambient plasma: inside the plasmasphere the density in the equatorial plane may ultimately decrease to 50-100 cm^{-3} while outside the plasmapause, where magnetospheric conditions do not favor ion containment, it may drop to 1-10 cm^{-3}. Complex discontinuities ("troughs") in the densities of ions in the topside ionosphere have been mapped by AE satellites (see section V-c) and they appear to be related to magnetospheric phenomena, at least in some cases.

The ionosphere has a complex structure. Early studies by means of radio sounders—instruments beaming radio signals upwards from the ground and measuring the delay between their transmission and their arrival of a reflected signal from the ionosphere—distinguished several regions on the basis of their electron densities, termed the D region (60-90 km), the E region (90-140 km), the F1 region (140-200 km) and the F2 region (above 200 km). In each such region ionization is attributed to a different part of the solar spectrum and/or to specific chemical processes which change in nature from region to region. The lower regions exhibit a large daily variation (e.g. the D region practically disappears at sunset) while the F layer distributions vary seasonally and over the solar cycle.

Unique conditions exist in the *polar ionosphere* due to the precipitation of auroral electrons from the magnetosphere (and on occasion, the precipitation of solar flare particles) and due to energy input from magnetospheric currents (Figure IV-15). The magnetospheric electric field (Figure IV-13) causes rapid flows in the upper polar ionosphere, which have been observed from satellites and also by means of artificial ion clouds (section VIII-d-4). Much remains to be learned about these effects and about the way in which they are linked to atmospheric processes at lower levels.

The *equatorial ionosphere* also exhibits an array of interesting phenomena, including the intense electric current along the geomagnetic equator known as the "equatorial electrojet", and irregular patches in the F layer termed "spread F" regions. The latter appear to be associated with a local plasma instability which produces huge rising "bubbles" in the ionosphere: the unstable plasma causes radio signals from communication satellites to scintillate (in a way resembling the twinkling of starlight) and interferes with their reception. Such "bubbles", their dimensions and possible trigger mechanisms which initiate them are to be studied extensively by the Wave Injection Facility (WIF) on Spacelab.

4 Solar Activity and the Atmosphere

Ever since the solar cycle was discovered, attempts have been made to correlate weather and climate with the

Sun's 11-year periodicity and with other solar "cycles"—in particular, the 27-day period of solar rotation (as viewed from the moving Earth), the 22-year "double sun spot cycle" and long-term variations in the average level of solar activity, such as the Maunder minimum (Figure IV-5). Here the 22-year cycle is obtained by regarding two consecutive sunspot cycles as a single period, since their large-scale magnetic patterns are not identical but have reversed magnetic polarities. In addition, attempts have been made to correlate atmospheric circulation and other weather changes with the "interplanetary sector structure" and with magnetospheric activity.
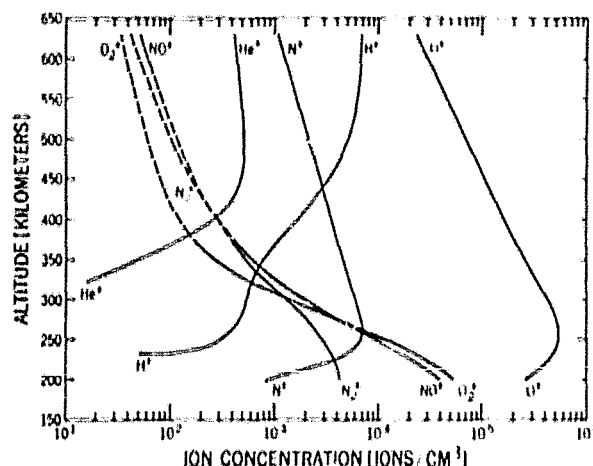
Fig. IV-25. Density profiles of various ion species in the Earth's Ionosphere.

Most results have been inconclusive, but some interesting links remain possible. The most pronounced among these is the cooler climate apparently associated with long term minima in solar activity (sect. IV-a-3 and ref. 25-2). Consistent correlations have also been found between the passage of interplanetary sector boundaries (Figure IV-10) and winter storms, expressed by a "vorticity area index", in middle northern latitudes (references 25-3, 25-4). Other tentative correlations have suggested a 27-day fluctuation in the 500 millibar level of the atmosphere, a 22-year periodicity (deduced from tree rings) of drought cycles in the high plains of the U.S. and a variation of mid-latitude thunderstorm frequency with solar activity.

Such phenomena, if they are confirmed, may be explained in one of two ways, and both possibilities will be investigated by the missions proposed in this plan. On one hand, the solar constant may vary slightly—for instance, it may rise and fall with the average level of solar activity. A

decrease of the order of 1% in this constant may be sufficient to produce the cooling associated with the "Maunder minimum"; by way of contrast, long term measurements of this quantity during the present century are only accurate within 1% - 1.5%. Instruments aboard SMM and Spacelab will initiate a continuous effort to monitor this constant with an accuracy of 0.1%.

Secondly, we already know that the short wave solar radiation such as the extreme UV and X rays, as well as phenomena in the solar wind and the magnetosphere, all vary significantly with solar activity and with solar rotation. The energy reaching Earth in these forms is only a tiny fraction of the solar energy arriving in visible sunlight, yet in certain regions this input dominates all others (see Figure IV-23), and this could increase its effect on the total atmospheric circulation beyond what simple energy considerations would suggest. Additional modes of linkage should also be considered: for instance, the passage of a sector boundary shifts the pattern of electric currents flowing in the polar ionosphere, altering the force which they exert and thus possibly affecting wind flow. Similarly, enhanced production of NO_x by solar and magnetospheric particles (Figure IV-22), leading to catalytic destruction of ozone, may perturb the middle atmosphere far more than the associated energy input might indicate.

If any such factors influence weather and climate, their chain of cause-and-effect inevitably leads through the middle atmosphere. With UARS and with the remote sensing instruments aboard Spacelab, the program outlined in this report should be in a good position to substantiate or refute a wide range of links which have been proposed between the active Sun and weather processes, and lead us to a more soundly based physical understanding of how the Sun controls our environment.

V. CURRENT AND RECENT MISSIONS

This chapter describes the current program for the study of solar-terrestrial relations recent and ongoing missions which form the basis for future plans, and planned missions which have received approval but have not yet been carried out. A list of unmanned scientific spacecraft involved in these missions together with details about their orbits can be found in Table V-1.

a. Solar Research

Currently planned solar observations from space are largely the outgrowth of the successful series of OSO (Orbiting Solar Observatory) spacecraft, culminating in OSO 7 and OSO 8.

(1) *OSO 7*, launched in September 1971, observed solar activity in UV, X rays and gamma rays, including the solar flares of August 1972, the largest in many years. Its observations at that time included the first detection of the characteristic gamma ray emission of heavy hydrogen at 2.2 Mev and other gamma ray "lines" at 0.51 Mev (from positron annihilation), 4.4 and 6.1 Mev, all confirming that flare processes imparted high energies to solar particles. Other observations of OSO 7 identified "coronal holes" and "coronal transients", further described below in connection with the Skylab mission.

(2) *OSO 8*, launched June 1975, observed the Sun during its low-activity period, using a pair of UV spectrometers with a resolution of 2" - 5" (it also carried X-ray detectors for astronomical studies and a UV monitor for the upper atmosphere). It provided extensive data about sound-wave oscillations of 30-350 seconds in the chromosphere, showing that they matched theories of large-scale solar oscillation modes previously observed in the photosphere but that they could not provide an adequate heating source for the corona, as had been suggested.

(3) The *Skylab* manned orbiting laboratory (1973-4) provided some of the most impressive solar observations, especially concerning *coronal "holes"* and *"transients"* (reference 22-6). Coronal holes are dark and relatively cool regions in the corona, in which magnetic field lines are "open" to interplanetary space, rather than arching back towards the solar surface. Such regions can only be observed clearly in the extreme ultra-violet or in soft X-rays; they were detected by OSO 4 and were studied in greater detail by OSO 7. However, the 9-month period spanned by the observations of Skylab provided a much more detailed picture and covered many wavelengths, corresponding to different kinds of highly ionized atoms found in the corona. Skylab established that coronal holes were the source of the fast streams of solar wind, of the type associated with recurrent magnetic storms on earth, and also that large stable "holes" existed in the corona above the polar regions of the Sun.

Table V-1: Some recent or current free-flying spacecraft which observe the solar-terrestrial environment.

Name	(other name)	launch date	Agency it not NASA	Perigee km	Apogee km	Period	Incli-nation	Mission, instruments and achievements
IMP 6	Explor. 43	3.13.71		242	197,000	3.91 d	28.7°	Tail fields, substorms, kilometric radio waves.
OSO 7		9.29.71		329	575			Coronal structure, X rays and γ rays from Sun.
S³	Explor. 45	11.15.71		224	27,000	7.82 h	3.5°	Ring current of Earth.
HEOS 2		1.31.72	ESA	359	238,000	5.44 d	90.2°	Magnetospheric cusp and boundary layers.
TRIAD		9.2.72	US Navy	743	838	100.6 m	90.1°	Electric currents along magnetospheric field lines.
IMP 7	Explor. 47	9.23.72		202.000	236,000	12.3 d	17.2°	Tail, bow shock, interplan. magn. field, substorms.
IMP 8	Explor. 50	10.26.73		197,000	237,000	12.13 d	28.7°	Same as IMP 7, also kilometric radio waves.
AE-3	Explor. 51	12.16.73		357	370	91.8 m	68.1°	Upper atmosphere, ion bulk velocity.
ATS-6		5.30.74		synchronous				Ring current particles.

Table V-1. (cont)

Name	(other name)	launch date	Agency if not NASA	Perigee km	Apogee km	Period	Incli-nation	Mission, instruments and achievements
Hawkeye	Explor. 52	6.3.74	NASA w. U. of Iowa	470	126,000	2.11 d	89.8°	Northern polar cusp.
OSO 8		6.22.75		544	559	95.7 m	32.9°	Solar and astronomical observations.
AE-4	Explor. 54	10.6.75		154	3,816	127 m	90.1°	Similar to AE-3.
S3-3		7.8.76	USAF	246	7,856	176.6 m	97.5°	$E_\parallel$ and particles accelerated by it.
GEOS 1		4.20.77	ESA	2,110	38,400	12 h	26.2°	Ring current, plasmapause. Mass spectra of ring current.
ISEE 1/2		10.21.77	NASA and ESA	280	145,000	2.4 d	28.7°	2 spacecraft, variable separation. Magnetosphere, bow shock.
GEOS 2		7.14.78	ESA	synchronous				Ring current, plasmapause.
ISEE 3		8.12.78		orbit around sunward libration pt.				Solar wind properties incl. composition, magn. field.

Skylab also observed huge coronal "transients" — bubble-like bodies of gas expelled by solar activity (Figure 1-2). Again, such transients had been recorded by OSO 7, but Skylab did so with superior clarity and detail. Skylab instruments also produced a wealth of high-resolution pictures of the Sun in selected UV and EUV wavelengths, which continue to help studies of processes which transfer energy in the solar envelope.

(4) NASA's next scheduled major solar study is the *Solar Maximum Mission* (SMM), to be launched in 1979. As the name suggests, this spacecraft is to concentrate on flares and similar high-energy phenomena on the sun, at the 1980 peak of the 11-year cycle of solar activity.

The basic idea of these observations is as follows. Flares and other manifestations of solar activity concentrate energy into hot regions and into fast particle beams, which become conspicuous by the emission of *short wave radiation* — UV, X-rays and gamma rays. Accordingly, SMM carries instruments covering this range, capable of resolving features of 3000-7000 km, i.e. subtending angles of the order of 4"-10" (except at the shortest wavelengths, corresponding to the highest energies, where such resolution is hard to attain: see the description of the proposed "Pinhole Camera" mission below). Different wavelengths, corresponding to various highly ionized atoms or to different energies of radiating flare particles, are also resolved, and the instruments can be steered to observe the same active phenomena simultaneously. SMM also carries a *coronograph* for observing coronal transients and a *solar constant* monitoring package, capable of detecting small changes in the Sun's overall energy output.

SMM is intended to be complemented by Spacelab missions, which will carry more powerful instruments but will have limited observing time. Weighing close to 2 tons, SMM will be the first mission to utilize NASA's *Multimission Modular Spacecraft* (MSS), a standardized large spacecraft incorporating sophisticated hardware for data handling and transmission, attitude control and propulsion. It is to be placed in a low earth orbit around an altitude of 575 km, and it may be retrieved by the space shuttle and refurbished for future missions.

b. The Heliosphere

(1) The solar wind in the earth's vicinity has been monitored by a long series of *IMP* (*Interplanetary Monitoring Platform*) satellites, with orbits which assured their being in the solar wind much of the time. At present, IMPs 7 and 8 are still operating in large near-circular orbits. Summaries of the IMP observations of solar wind plasmas and interplanetary magnetic fields have been published by the National Space Science Data Center and are widely used for basic correlations between the solar wind input and near-earth phenomena.

(2) *Planetary missions*, especially Pioneers 10 and 11, and Voyagers 1 and 2 — although not primarily part of the Solar Terrestrial Program, observe interplanetary phenomena while in their "cruise mode":

The *Pioneer spacecraft*, in particular, have extended our data base to distances of about 10 astronomical units (one AU equals the mean Sun-earth distance). They have shown that:

- the rate at which galactic cosmic ray intensity increases, with growing distance from the Sun, is far smaller than had been theoretically predicted,

- that at large distances from the Sun, boundaries of fast solar wind streams steepen to form shock discontinuities, and

- that the interplanetary magnetic field is disk-like and seems to be stretched out in the Sun's equatorial plane (Figure IV-9).

(3) *ISEE-3*, the 3rd spacecraft in the ISEE (*International Sun Earth Explorer*) mission (described further below) was launched on August 12, 1978, toward a "halo orbit" around the Sun-earth libration point, a point of gravitational equilibrium on the Sun-earth line, about 0.01 AU distant. Unlike the IMP spacecraft, ISEE-3 will be in the interplanetary medium at all times, upstream of the earth's bow shock.

The instruments aboard ISEE-3 include mass spectrometers for accurate analysis of the composition of the solar wind. Other instruments measure ion and electron energy distributions, magnetic fields, radio waves, low frequency plasma waves and properties of interplanetary particles ranging in energy from those typical of the solar wind up to the cosmic ray range, including particles accelerated in solar flares and perhaps also some which are energized in interplanetary space or in planetary magnetospheres.

c. The Magnetosphere

Because the magnetosphere is large and complex, its study requires simultaneous observations at different locations. When a magnetospheric substorm occurs, for instance, observations in interplanetary space, in the polar cusps, in the plasma sheet, several earth radii above the auroral zone, in the ring current and above the polar ionosphere (Figure IV-12) all will complement each other.

This has led to two trends. *First*, magnetospheric research tends to involve *many separate spacecraft*, and even instruments aboard spacecraft which were intended for other purposes can play an important role: the particle detectors on Applications Technology Satellite (ATS) 6 were the first to detect in synchronous equatorial orbit electron beams accelerated from the ionosphere, and the magnetometer aboard the Navy's navigation satellite Triad has provided a major portion of our initial information about electric currents coupling the magnetosphere with the ionosphere. For the same reason, magnetospheric research stresses collaboration between different spacecraft projects, inside and outside NASA and even on an international scale.

A *second* and related trend is towards co-ordinated, problem-oriented missions involving *multiple spacecraft* — three for ISEE, two for AMPTE and two for DE (all these missions are described below). The final number of spacecraft in the proposed OPEN project is not yet decided, but it will probably be at least 4.

Recent and current missions include:

(1) *IMPS 6, 7 and 8*. These last spacecraft of the IMP series greatly expanded our information about *substorms* in the plasma sheet of the magnetotail (Figure V-1) and about associated plasma flows, magnetic field variations and high-energy particles. The radio wave experiments on IMP 6 provided the first complete measurements of the
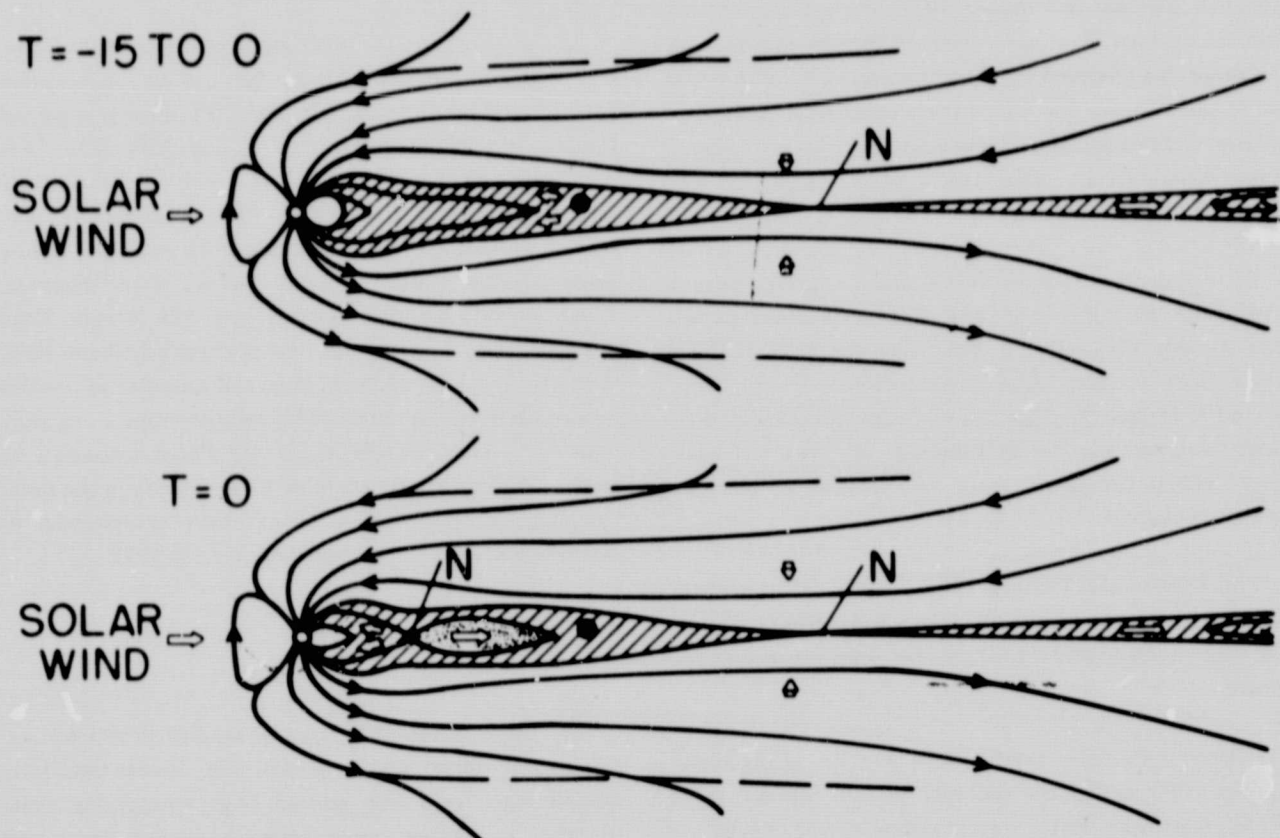

Fig. V-1. Changes in the magnetospheric tail configuration during a substorm, as deduced from observation by IMP 6.

intense auroral *"kilometric radiation"* (with wavelengths of the order of a kilometer) emanating from above the auroral zone, and these observations were continued by IMP 8.

(2) *ATS 5 and 6*, although primarily applications technology satellites, monitored the ring current (Figure IV-12) in synchronous orbit, detected *"plasma clouds"* injected by substorms and also beams of electrons accelerated along magnetic field lines.

(3) *Hawkeye* an explorer spacecraft developed and operated by the University of Iowa, provided detailed observations of the polar cusp and its plasmas, a region where much of the initial coupling between the solar wind and the magnetosphere apparently takes place.

(4) The *ISEE 1+2* (International Sun-Earth Explorer 1+2) mission consists of two spacecraft with onboard propulsion, enabling them to vary their mutual separation from 100 to 5000 km. ISEE-1 was built by NASA, ISEE-2 by the European Space Agency (ESA), and both were launched together in October 1977. The variable separation has enabled these spacecrafts to determine, which of the variations observed by them are caused by motions in the magnetosphere and which ones represent irregularities in the 3-dimen... structure of the magnetosphere. Single spacecraft are often unable to tell the difference, especially over small distances.

By timing the passage of the dayside magnetopause and bow shock past the two ISEE spacecraft, investigators have already succeeded in measuring the velocity with which these features "flap in the solar wind" typically, around 6 km/sec. Further measurements are expected to yield two-point correlation functions of flows and magnetic fields in the plasma sheet, an important property of turbulent plasmas.

The mission also includes ISEE-3, designed to provide correlated observations of the solar wind and described in the section on current missions for studying the heliosphere.

(5) *Dynamics Explorer* (DE), to be launched at the beginning of 1981, will utilize two spacecraft in coplanar polar orbits. One spacecraft, in a low-altitude near-circular orbit, will observe magnetic and electric fields, electric currents along magnetic field lines and plasma flows. These

observations will make it possible to trace the processes which couple the magnetosphere and the polar ionosphere and to measure the energy flow carried by particles and currents from the magnetosphere into the atmosphere.

Other instruments on the low-altitude DE spacecraft will survey the composition and temperature of the thermosphere and the flow of thermospheric atoms and ions. In this respect, DE will continue the studies of the AE series (see below), but with the advantage of being able to observe both magnetospheric inputs and their effects on the atmosphere.

The high-altitude DE spacecraft will move in an eccentric orbit with near-earth perigee but with an apogee of about 6 earth radii. In addition to detectors for analyzing the energy and mass of ions, this spacecraft will also carry a plasma wave experiment, a magnetometer and an imaging instrument for viewing large-scale auroral formations from above, observations which can then be correlated with passages of the lower spacecraft through the same formations.

As noted before, the STP effort in magnetospheric research is coordinated with studies conducted by other agencies and by other nations. The ISEE mission is part of the International Magnetospheric Study (IMS) of 1976-9, which also involves ESA's GEOS 1 (1977) and GEOS 2 (1978), as well as the Japanese EXOS spacecraft, concerned primarily with the exosphere (sect. IV-d-2). Noteworthy recent contributions to studies of the magnetosphere were also provided by the US Navy's Triad (launched 1972) and by the US Air Force's S3-2 and S3-3, the latter of which observed beams of ionospheric protons and oxygen ions accelerated by voltage drops along magnetic field lines. SCATHA, an Air Force spacecraft to study the electrostatic charging of spacecraft in the outer ring current and carrying an extensive complement of instruments, is due to be launched in early 1979.

d. The Upper Atmosphere

The upper atmosphere can be studied in-situ by satellites only down to about 130 km. Below that level observations from the ground (e.g. ionospheric radio sounding or airglow measurements), from balloons and from sounding rockets have provided most of our information. Instruments for remote monitoring of the upper

atmosphere from space are relatively recent and only the proposed AMPS and UARS missions (further described elsewhere in this plan) will begin utilizing them on a large scale.

Current missions include:

(1) The *Atmosphere Explorer* (AE) program included 3 spacecraft in low altitude orbits (Table V-1): AE-3 (launched 12/73), AE-4 (10/75) and AE-5 (11/75). These spacecraft carried on-board propulsion, enabling them (for brief intervals) to sample the atmosphere down to about 130 km, and they also employed a versatile data system, linked to a computer on the ground so as to make newly acquired data available to the investigators with a minimum of delay (not exceeding 10 days and on occasion only a few hours). The proven AE design concept will also be followed to a large degree by the DE spacecraft, which will continue some of the observations of the AE program.

The AE program has provided global in-situ observations of the thermosphere—the composition and temperature of both its ionized and neutral components, the extent of "troughs" which develop in it and other features. Among its specific observations:

Global mapping of nitric oxide (NO), observing the enhancement of NO in the auroral zone following the precipitation of energetic particles. Enhanced production of NO may possibly lead to ozone depletion associated with solar activity.

Extensive information about ionic reactions in the thermosphere (reference 25-10). Because special conditions prevail in that region, such rates were often found to differ from those predicted by laboratory experiments.

Extensive observations of selected regions of the solar UV spectrum and its absorption by the atmosphere. Such observations will be expanded by the occultation mode of SME (below).

Observations of the density and upward flow of neutral hydrogen in the exosphere. This flow is the source of a huge cloud of neutral hydrogen surrounding the Earth (Figure IV-24), which plays an important role in the removal of energetic protons injected into the terrestrial ring current during magnetospheric substorms.

(2) The *Solar Mesophere Explorer* (SME), to be launched in 1981, is designed to observe the concentrations of two active minor constituents of the mesosphere, namely ozone (O_3) and NO_2 (although most of the terrestrial O_3 is stored in the lower stratosphere, its origin is general in the upper part of the stratosphere, near the boundary of the mesosphere). The concentration profile of these constituents will be obtained with an altitude resolution of about 3.5 km, using the absorption and also the re-emission of sunlight near the horizon as viewed by the spacecraft ("solar occultation method"). This will be correlated with variations of the solar ultraviolet flux, which will be monitored aboard SME between 1600 A and 3100 A.

SME will also measure infra-red emissions as follows:

From CO_2 at 15μm, to determine temperature and pressure between 30 km and 75 km.

From ozone at 9.6μm, to determine its density between 25 and 65 km.

From water vapor at 6.3μm, to determine its density between 30 and 65 km. Water vapor in the upper atmosphere splits up into active components which react with ozone.

From O_2 at 1.27μm, giving the photodissociation rate of O_3 between 50 and 90 km.

(3) The *Dynamics Explorer* mission (DE), to be launched in 1981, includes a low altitude spacecraft (DE-B) which, in addition to other tasks, will carry instruments to extend the work of the AE mission. It will carry a mass spectrometer for neutral atmospheric constituents, a spectrometer for sensing winds locally and a Fabry-Perot interferometer for sensing them remotely. Furthermore, it will also use Langmuir probes and retarding potential analyzers to measure local electron and ion temperatures (respectively), and these will be correlated with the magnetospheric energy input due to precipitating auroral particles and due to electric currents, both of which will be measured by the same spacecraft.

VI. PROPOSED MISSIONS — OVERVIEW

a. The Transition from Exploration to Detailed Study

Early space missions were mostly exploratory, designed to probe new regions for the first time and to offer a first look at new phenomena. In the time frame 1980-1985 our ambitions extend further: with some notable exceptions (e.g. the distant geomagnetic tail) the initial qualitative probing is complete and we have derived tentative models for all parts of the solar-terrestrial environment. The next step is to understand the processes which govern these regions—for instance, the processes responsible for energy release in solar flares and in magnetospheric substorms, or for the large-scale flow and energy balance in the middle atmosphere.

How does one proceed? The proven way, and the one used in this plan, is to rely on the past as a guide to the future—*to follow up and exploit successes and promising leads*, derived from recent missions which have studied the solar-terrestrial environment.

Consider for instance the *Solar Polar* mission. Following the Skylab observations it became clear that "coronal holes" were intimately connected with the origin of the solar wind and with the "sector structure" of the interplanetary magnetic field, a structure which has notable effects on the magnetosphere and perhaps even on the atmosphere. Skylab also made clear that "semi-perma-

nent" coronal holes covered the Sun's polar regions, and some time afterwards Pioneer 11 provided evidence that the interplanetary magnetic field was stretched out (at least some of the time) in a disk-like fashion (Figure IV-9).

It thus became evident that both the solar wind and the interplanetary magnetic field above the Sun's poles were qualitatively different from those observed near the Earth's orbital plane. The Solar Polar mission then became the logical next step: in some ways it is an exploratory mission to a new region in space, but it is not a stab in the dark, because previous missions have already given us clues about what might be expected, and the planning of orbits, selection of instruments and related theoretical studies were all guided by such clues.

Most of the other missions proposed here also represent the logical evolution of instruments and models from previous successful missions to new areas of observation:

- AMPTE (*Active Magnetospheric Particle Tracer Experiment*), with its active plasma releases, utilizes experience gained in barium vapor releases from sounding rockets, in the ionosphere and on occasion also in more distant parts of the magnetosphere. In its turn, AMPTE will test the usefulness of distant ion releases for tracing magnetospheric motions and plasma entry and will thus prepare the way for more

sophisticated active experiments from Spacelab (see sect. VIII-d-4).

OPEN (*Origin of Plasmas in the Earth's Neighborhood*) will follow-up on observations of the terrestrial ring current i y GEOS and by other spacecraft (including the Charge Composition Explorer of AMPTE), tail observations by the IMP series and inputs from the ISEE mission, DE, S3-3, Hawkeye, HEOS and others. One important advantage will be that many observations, for the first time, will be performed *simultaneously* in different parts of the magnetosphere, making it possible to study the ways in which processes in different regions of the magnetosphere are coupled to each other. One of the spacecraft envisioned by OPEN is the *Interplanetary Physics Laboratory* (IPL), a successor to ISEE-3 which pioneered mass-spectrometer measurements of solar wind composition and was itself a follow-up on the IMP series.

— The forthcoming UARS (*Upper Atmosphere Research Satellite*) mission and related Spacelab flights are both an outgrowth of a long and successful development of technology suitable for remote sensing of the middle atmosphere. The UV backscatter measurements of ozone, for instance, will be an outgrowth of those of Nimbus 4 (Figure IV-22), while CLIR (sect. VIII-d-2) will be following a successful series of helium-cooled instruments (HIRIS, IRBS) flown aboard sounding rockets by the US Air Force. In future developments of this technology, Spacelab will probably serve as a "testbed" for initial flights of instruments meant to be incorporated in follow-on UARS missions.

b. The Space Shuttle

While the missions proposed here represent a natural evolution of current achievements, there also exist important innovations. The most significant of these involves the use of the *Space Shuttle*, which in the 1980s is to become the mainstay of NASA's launch operations.

The orbiter of the Space Shuttle (Figure II-1) is a reusable manned spacecraft, capable of carrying a payload of 30 metric tons into low earth orbit. Launch is assisted by two large solid-fuel rockets and by a large external fuel tank feeding the Shuttle's rocket engines, while at the end

of each mission the orbiter reenters the atmosphere under control and uses its wings to land on a runway in the manner of a conventional aircraft.

The cargo bay of the Shuttle is 60 feet long and 15 feet in diameter (18.3 by 4.6 meters), and it can carry several payloads in a single flight. When the Shuttle serves as a launch vehicle, most such payloads are expected to carry their own propulsion units, for the planned insertion orbit at 300 km is a relatively low one and orbital lifetimes in it are short.

The *Spacelab orbiting laboratory* carried aboard the shuttle for conducting scientific experiments in space, is a major component of this 5-year plan and a special section (the next one below) is therefore devoted to it. In addition to Spacelab, many other accessories and options are planned for the Shuttle in order to make the best use of its capabilities. Launches from the Shuttle into higher orbits will utilize a choice of standard launchers—*Spinning Solid Upper Stage* (SSUS) A or D (with different payload capacities), or the *Inertial Upper Stage* (IUS). All spacecraft launched into orbits below the synchronous orbit at 6.6 earth radii are expected to transmit their data not to a ground tracking network but rather to one of the two relay satellites of the *Tracking and Data Relay Satellite System* (TDRSS).

It has been suggested that the Shuttle may retrieve spacecraft such as SMM from near-earth orbits for refurnishment or repair. An unmanned *"space tug"* is also being considered, to perform retrieval of more distant satellites, e.g. those in synchronous orbit: it would rise from the Shuttle, rendezvous with the appropriate spacecraft, attach itself and finally, return to the Shuttle's cargo bay. Another concept being actively studied is the *Solar Terrestrial Observatory*, an unmanned space station enabling large facility-type instruments, such as those planned for the Spacelab program, to operate in orbit for long stretches of time. The observatory would operate independently but will be visited periodically by the Space Shuttle for the exchange of instruments, maintenance, recovery of film and special observations which require direct human control.

Current plans call for 6 initital test flights of the Space Shuttle in 1979-80, some of which will carry limited scientific payloads. After this the Shuttle is to begin a regular schedule of launches, which is expected to reach about 60 per year.

c. Spacelab

The Space Shuttle is not only scheduled to become NASA's standard launch vehicle, but it will also be used to carry an *orbiting laboratory* to perform in situ experiments in space, in sorties lasting 7-28 days.

This orbiting laboratory, named *Spacelab*, represents a cooperative effort which began in 1972 between NASA and the European Space Agency (ESA). ESA has developed and built two Spacelab units, including pressurized cabins with laboratory space and supporting equipment (e.g. power, computers and data handling), to be carried when necessary in the Shuttle's cargo bay and to be entered through a tunnel from the crew section of the Shuttle (Figure II-1).

In the Spacelab mode, the Shuttle can carry 5000-9000 kg of instruments, on pallets attached inside the cargo bay, and special supporting equipment is also being planned e.g. an articulated boom (supplied by Canada) capable of manipulating payload packages some distance away from the cargo bay and also used in the retrieval of free-flying subsatellites. The first test flight of Spacelab is scheduled for the middle of 1981.

The Spacelab cabin follows a flexible design and uses either a single basic cylindrical shell or two such shells joined together: the latter configuration doubles the amount of pressurized work space but it also reduces the available work area in the open cargo bay, since the cabin must be placed a considerable distance to the rear in order to maintain the overall center of gravity. With a single cabin-shell up to 3 pallets can be accommodated in the cargo bay and when no cabin is used, up to 5. The cabin is designed so that entire self-contained rack assemblies can be rolled into it and off it, allowing for a rapid turnaround of onboard equipment and making it possible to check out and integrate much of the equipment beforehand.

For the Solar-Terrestrial Program two main uses of Spacelab are contemplated - as a *solar observatory* and in the AMPS program (*Atmosphere, Magnetosphere and Plasmas in Space* program). The solar observatory will eventually include at least 3 large facilities, complemented by a number of smaller, special purpose instruments: each facility will cover a different spectral range, with the Solar Optical Telescope (SOT) using conventional mirror optics, an extreme ultra violet (XUV) telescope using grazing-incidence reflection and a hard X-ray imaging system based on the use of multiple collimators (these are all described in section VIII-e).

The AMPS program, as its name suggests, will investigate several classes of phenomena. Electron beams are to be released from Spacelab in order to trace magnetic field lines and field-aligned voltage drops and also to investigate the interaction of such beams with the ionosphere plasma. Releases of barium vapor and perhaps also of cold gas are envisioned, experiments are planned for studying the propagation of plasma waves and LIDAR (*Light Detection and Ranging*) is to be used extensively in probing the atmosphere by means of laser light. In addition, sensitive spectrometers and other detectors for the characteristic infra-red emissions of constituents of the upper atmosphere will be carried, cooled down by liquid helium in order to increase their sensitivity.

Two modes of operation are expected for Spacelab. For some studies, proposals for specific observations or experiments will be solicited from scientific teams and those teams which are chosen will be given full responsibility for the design and operation of their instruments. These are termed "principal investigator" class experiments. Some types of apparatus, however, serve a wider range of applications and require a greater supporting effort: such instruments will be regarded as *scientific facilities* and will be made available to various scientific workers as the need arises. A number of such facilities are currently under study, and they are described in more detail in chapter VIII.

VII. PROPOSED MISSIONS — FREE FLYING SPACECRAFT

a. Sun and Heliosphere

1 Solar Polar Mission and OPEN

i. The Solar Polar Mission

This mission, proposed for a 1979 start and a 1983 launch, is planned as a joint venture with the European Space Agency (ESA), with NASA and ESA providing one spacecraft each. The combined payload of the two spacecraft will be divided between US and European investigators in proportion to the relative financial contributions of the two collaborating agencies.

The Solar Polar mission will provide a *first look into a region never previously explored*. Up till now, in-situ studies of the heliosphere were limited to the vicinity of the earth's orbital plane, the plane of the ecliptic. The reasons were both technical and practical: a considerable amount of extra rocket thrust is required to send a spacecraft far outside the ecliptic, and all planets which have served as targets for interplanetary missions are found ⟶ ⟶ to that plane.

However, as was noted in section V-b, it now appears that the solar wind and related interplanetary properties above the Sun's poles differ considerably from those existing near the plane of the ecliptic. This difference provides the main motivation for the mission, which was originally known as the "Out of Ecliptic" (OOE) mission.

To acquire a large velocity component directed away from the plane of the ecliptic, both Solar Polar spacecraft will utilize the gravitational pull of the planet Jupiter. They are to be launched simultaneously by the Shuttle and will then be boosted towards Jupiter by an Inertial Upper Stage (IUS). Reaching Jupiter 1.3 years after launch, one spacecraft will be targeted for a gravitational swing over the northern Jovian pole and the other over the southern one. These gravitational swing-by maneuvers will direct the two spacecraft out of the ecliptic plane and into elliptical trajectories which are essentially "mirror images" of each other (Figure VII-1).

The spacecraft will pass simultaneously over the northern and southern solar poles, respectively, about 2.5 years after the Jovian encounter, at a distance of 1.3 Astronomical Units (1 AU = mean Sun-earth distance). Each spacecraft then crosses the plane of the ecliptic and passes above the other solar pole before heading back towards Jupiter's orbit. Thus there will exist two periods, roughly 6 months apart, during which the two spacecraft will view opposite poles of the Sun. The two spacecraft will be tracked until about 8 months past their second polar passage, for a total mission duration of about 5 years.

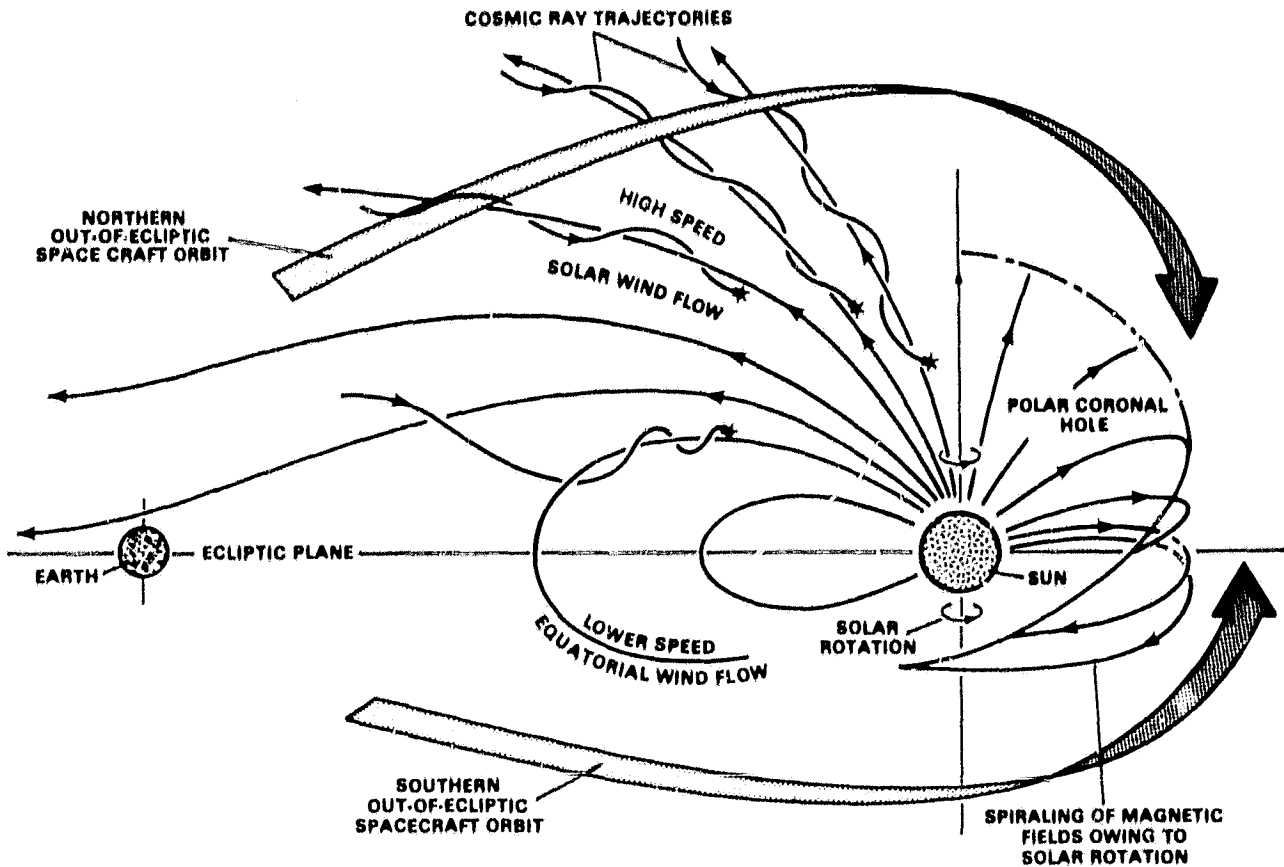What can be expected to be learned from the Solar Polar Mission?

Fig, VII-1, A schematic view of the Solar Polar mission.

It has already been noted that the Sun's polar regions resemble "coronal holes", with "open" magnetic field lines which allow easy outflow of solar wind. If such "polar holes" affect the flow of the solar wind in the same way as "holes" from which magnetic field lines extend to the vicinity of the Earth, they ought to be the source of a relatively smooth interplanetary magnetic field which is not grossly twisted by solar rotation.

But the polar magnetic field lines may well be also "open" in a different sense—in the sense that polar field lines of the *Earth* are "open". Terrestrial "open" field lines are directly connected to the interplanetary magnetic field, and in the cusp region (Figure IV-12) interplanetary particles may be guided along them deep into the magnetosphere. A similar connection might exist between "open" solar polar field lines and *interstellar space*, so that the Solar Polar spacecraft may observe interstellar cosmic ray particles without the modulation which is

known to reduce their density near the plane of the ecliptic.

The Solar Polar mission can also attack related problems involving the flow of high-energy particles—e.g. the 3-dimensional structure of transient reductions in cosmic ray intensity following solar flares ("Forbush effect"), or the propagation of energetic particles from flare regions, which is expected to be different near the poles and near the ecliptic. The availability of two distinct spacecraft greatly extends the baseline of such studies: for instance, when solar activity is enhanced in a limited region on the sun, effects observed above the pole of the hemisphere where the activity has occurred probably differ significantly from those seen above the opposite pole.

During the cruise towards Jupiter, with the spacecraft some 0.02 AU apart, measurements can be made of small-scale variations in the solar wind on a scale comparable to

the spacecraft separation. From the Jovian fly-by, new information is also expected concerning the environment and the radiation belt of the planet Jupiter, especially about the polar regions of the Jovian magnetosphere.

The two spacecraft will not be identical, although both will carry magnetometers and also particle spectrometers for measuring the energy and composition of the solar wind. Additional experiments will observe cosmic rays and energetic solar particles, cosmic gamma ray bursts (a high-energy astrophysics experiment), interplanetary plasma waves and radio emissions, solar X-rays and extreme UV emissions, as well as other phenomena.

A white-light coronograph will observe from afar the overall configuration of the Sun's corona in the plane of the ecliptic, which ought to be related to simultaneous observations by spacecraft near Earth (such as IPL, below). A reciprocal observation of this kind will be performed by SCADM, observing the corona in a plane containing the solar axis at the same time when the Solar Polar spacecraft will be observing in-situ conditions in that plane.

II. The Interplanetary Physics Laboratory (IPL) of OPEN

This spacecraft is one of the components of the OPEN mission, in which it is meant to play a role similar to the role of ISEE-3 in the ISEE mission. The OPEN study of the Earth's magnetosphere, described below in more detail, is scheduled for a 1982 start and for launches to begin in 1985.

Like ISEE-3, the Interplanetary Physics Laboratory will have two distinct objectives:

- In its primary function, it is an *essential component of the OPEN study* of the Earth's magnetosphere, providing simultaneous information about the state of the solar wind and the interplanetary magnetic field. Such information is essential, since magnetospheric phenomena appear to be energized by the solar wind and are profoundly affected by interplanetary conditions.

- Independently of this monitoring function, IPL is also to *study the solar wind* in the Earth's vicinity. The information obtained can then be compared with theory or correlated with measurements of the Solar Polar spacecraft, or with solar observations such as those performed by SCADM and Spacelab.

Details of the OPEN mission are still being worked out and the instrumentation of IPL, too, is still in the planning stage. The support function of IPL will certainly require detectors for plasma density, velocity and temperature, as well as energetic particle detectors and sensitive magnetometers. Several important options exist beyond this, but probably the most significant of these is instrumentation for better resolution of *solar wind composition*.

Indirect studies of the composition of the solar wind have utilized peaks in the energy spectrum that is, they have assumed that the solar wind moved at a uniform speed and ascribed peaks in the energy distribution, at higher energies, to heavier nuclei in the solar wind. ISEE-3 is the first spacecraft to carry a mass spectrometer, capable of resolving different components directly, but there still remains an ambiguity due to the simultaneous presence of *different ionization states*, since the ISEE-3 instrument is sensitive not to the masses of the particles intercepted by it but only to their mass/charge ratio.

Future studies of the solar wind, by IPL or its successors, will try to resolve both the mass and the charge of heavier components in the solar wind. The relative abundance of different degrees of ionization (e.g. iron ionized 8, 9, 10 or more times) can serve as a "thermometer" to trace the temperatures of coronal regions in which the observed particles have originated. Furthermore, when "temperatures" derived from different components are compared, one can begin deriving theoretical models about the vertical structure of such regions of origin and in this way help develop an accurate theory of solar wind origin.

Other observations of the heliosphere which may be considered for IPL and its successors include

- Detailed measurement of the composition and energy of *higher energy particles* (up to about 1 MeV) accompanying the solar wind. Again, the distribution of ionization levels in such particles furnishes a clue about their origin and may be compared to that of the solar wind. The effect on this population due to the passage of shocks and turbulent regions—which might be their source of extra energy—can also be studied.

Similar measurements on the *"anomalous" heavier ions* between 1 and 30 MeV, which may be either galactic (like cosmic rays) or solar: if they are found to be completely ionized, they are probably galactic, if not solar. The instruments used for this task can also observe *energetic particles from solar flares* and by analyzing their composition, learn about their origin.

Neutral interstellar atoms are not affected by the solar wind or by interplanetary magnetic fields, and can easily penetrate into the heliosphere. A long-range project, for which instruments still require further development, is the direct measurement of such particles, especially of elements heavier than hydrogen.

2 Solar Cycle and Dynamics Mission (SCADM)

While there exists great interest in the violent energy release events accompanying high levels of solar activity (which are to be studied by SMM), there also exist many reasons for studying the Sun during times of moderate activity, between the peaks of the 11-year cycle. These include:

The need to measure the solar energy output throughout the entire cycle.

The observation of solar surface oscillations, undisturbed by active regions and their complex magnetic fields: these provide information about the solar convective layer beneath the surface.

Coronal holes, rapid solar wind streams and other phenomena which are most conspicuous between periods of peak solar activity.

To provide such data, the Solar Cycle and Dynamics Mission (SCADM or "Scadam") is proposed for launch in 1985. This mission will also provide continuous coronal observations by means of coronographs using white light and the UV spectral line of hydrogen at 1216 A (Lyman alpha line) for the Solar Polar Mission, which will meanwhile be passing high above the Sun's poles. SCADM will also complement SOT and other solar Spacelab instruments, and is expected to advance our knowledge about the origin of the solar wind, the Sun's corona, convective motions and magnetic fields in the outer layers of the Sun.

SCADM is undergoing a preliminary system design study and like SMM will use a Multimission Modular Spacecraft. It will be launched by the Space Shuttle and will be fully checked out in the Shuttle's vicinity before being boosted by an on-board engine to an altitude of 575 km. At the end of its mission SCADM is to be retrieved, and possibly to be refurbished and reflown. As noted elsewhere, a similar reflight is considered for the SMM spacecraft: it is possible that if SMM is retrieved early enough, parts of it may be used for SCADM, but because of schedule limitations, the SCADM mission is planned independently of the retrieval of SMM.

3 Solar Probe

Up to now the closest approaches to the Sun by terrestrial spacecraft were those of Mariner 10 which flew 3 times by the planet Mercury (perihelion 0.39 AU), and by the two European Helios spacecraft, which penetrated within 0.30 and 0.28 AU of the Sun. Missions to the immediate vicinity of the Sun require an appreciable thrust and must cope with the high temperature environment near the Sun, but they also hold the key to several problems, such as:

The generation of the solar wind.

The oblateness of the Sun due to rapid core rotation.

Small modifications of the motion of spacecraft in the strong gravity field near the Sun, predicted by the general theory of relativity.

Accordingly, a *Solar Probe* mission, designed to approach the Sun within 4 solar radii ($\approx$ 0.02 AU), is being studied for a possible start in 1983 and launch in 1986.

To enable a spacecraft which has escaped the Earth's gravity field to hit the Sun, an extra velocity of 30 km/sec is required, cancelling the Earth's orbital velocity, and this exceeds the velocity needed for escaping the solar system. The thrust requirements of the proposed Solar Probe are not much smaller, and two alternative methods for meeting them are being considered:

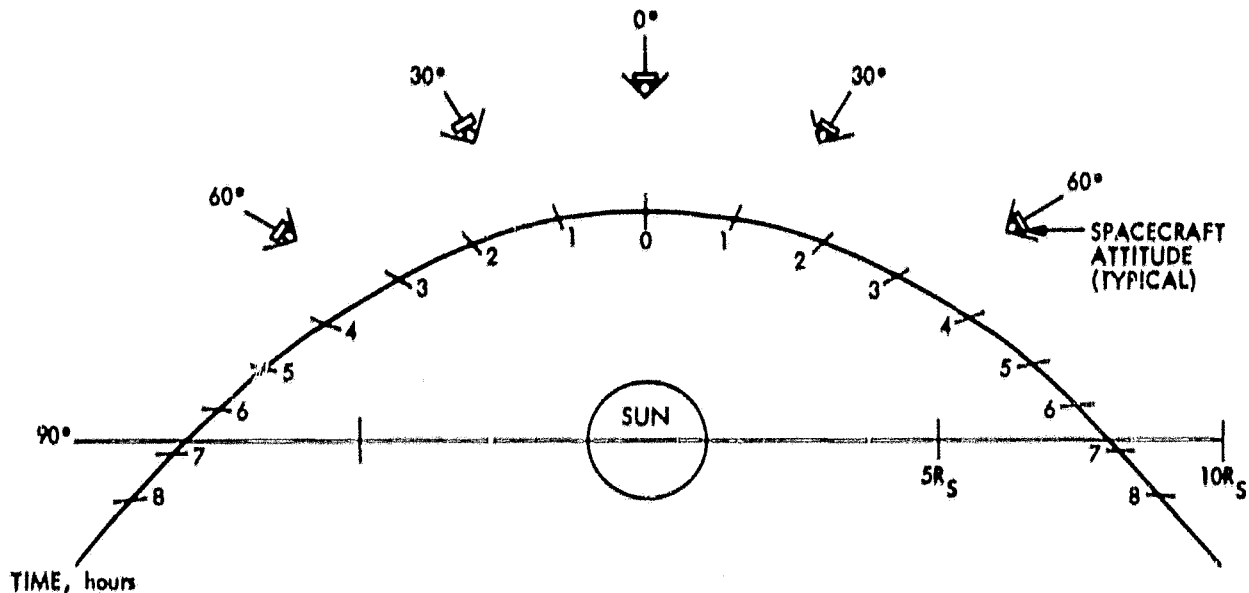The use of a gravitational boost from the planet Jupiter.

Fig. VII-2. The trajectory of the solar probe near the Sun, with marks at hourly intervals (0 indicates the point of closest approach). The spacecraft rotates in order to enable its heat shield to face the Sun at all times.

A low-thrust ion engine powered by solar cells and operating over a relatively long stretch of time.

The spacecraft will be shielded from solar heat by an "umbrella" facing the Sun and will spend about 20 hours within 10 solar radii of the Sun (Figure VII-2). At its time of closest approach, the Solar Probe will be the fastest man-made object ever to go into space and its velocity may exceed 300 km/sec. If the instruments continue functioning for a sufficiently long time, several passes near the Sun can be accomplished especially if ion propulsion is used, since the final orbital period can then be as short as one year.

Observations by the Solar Probe are expected to shed light on the origin of the solar wind. A general hydrodynamic theory exists for the accelerated outflow of gas from a hot corona, but it contains many discrepancies and problems—insufficient energy is predicted for the final flow, and the phenomenon is greatly modified by the solar magnetic fields responsible for "coronal holes." The solar probe may furnish the first in-situ observations of the acceleration region of the solar wind and the first direct measurements of its particle flows and magnetic fields. Plasma waves and turbulence in this region are also of great interest.

The spacecraft will contain a sensitive accelerometer—a completely enclosed test body, its motion strictly governed by solar gravity and shielded from disturbing effects such as the pressure exerted by particles or by sunlight. Control jets would provide the main spacecraft with the small amount of extra thrust needed for keeping up with the test body.

The observations of this instrument, coupled with accurate radio ranging, can accurately measure small changes in the spacecraft's motion due to solar oblateness or general relativistic effects. Solar oblateness due to rapid internal rotation of the Sun has been suggested on theoretical grounds, as a possible alternative explanation of effects ascribed to general relativity, but the effect is too small to be reliably observed visually from earth.

4 Pinhole Camera Mission

In studies of flares and of active solar regions, *short wavelength radiation* is regarded as the "signature" of high energy particles. The shorter the wavelength, the higher is the energy: UV, extreme UV, X rays and gamma rays indicate increasingly energetic portions of the particle population being produced.

Unfortunately, the shorter the wavelength, the more difficult does it become to *obtain an optical image* of the emitting region. Mirror telescope optics can be used in the UV range and special mirror instruments, in which all reflections occur at very shallow angles, have extended the optical range to that of soft X-rays. The arrival directions of *hard X-rays and gamma rays*, however, can only be deduced by using masks and baffles, as is being planned for the HXII facility on Spacelab. For images of better quality, only the pinhole camera principle remains—obtaining an image when the object is covered by a large mask, through which only a small hole allows radiation to pass.

The *Pinhole Camera mission*, now under active study, proposes to use this principle for obtaining high resolution images ($\approx 1'' \cdot 2''$) of solar active regions in hard X rays and gamma rays, at the time of maximum solar activity around 1990.

The mission is schematically depicted in Figure VII-3. A large mask covered with lead or tungsten will be carried aboard the Shuttle into an orbit aligned with the dawn-dusk meridian of the earth. The mask will contain a large number of pinholes, to increase the intensity available for observation—the resulting image is then no longer sharp, but a "normal" image can be recovered from it by suitable computer processing.
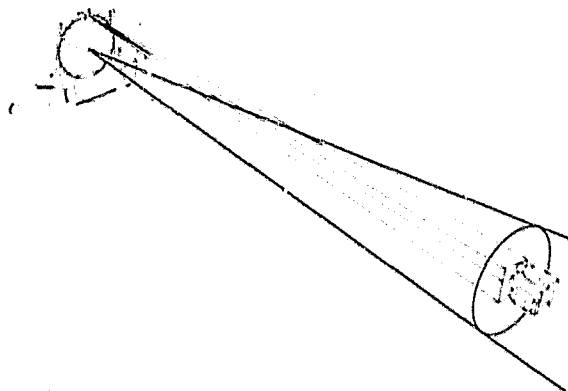

Fig. VII-3. Schematic view of the Pinhole Camera mission.

Orbiting in a parallel plane about 1 km distant will be a *detector satellite*, carrying an array of X-ray and gamma-ray sensors, as well as a propulsion system and a station-keeping control system utilizing laser beams, to make sure that the mask continually covers the solar disk as viewed from the satellite. The orbital plane of the detecting satellite does *not* pass through the center of the earth, but is offset from it by 1 km, and thus the propulsion system must be used throughout the mission—a total of 1500 kg of propellant is estimated to be needed for every week of observation time.

The pinhole mission will utilize pallets and other support equipment from Spacelab. The mask will be stowed aboard the Shuttle in a folded configuration and after the detector satellite has been released, it will be deployed to its full size, with a total diameter of the order of 10 meters.

b. Magnetosphere

1 Active Magnetospheric Particle Tracer Experiment (AMPTE)

It is commonly accepted that the energy driving active magnetospheric phenomena such as substorms comes from the solar wind, as does as a large fraction of the particles involved in such phenomena. *How do solar wind particles enter the magnetosphere?* One way for finding out is to inject into the solar wind "tracer ions" of a type rarely found in nature, see whether such ions turn up inside the magnetosphere and if so, where and with what energies.

This, in essence, is the aim of the *AMPTE mission*, which plans *to inject lithium and europium ions* into the earth's environment. Some of the material will be released in the solar wind, near the point where it first encounters the earth's magnetosphere, and the rest will be released in the near-earth plasma sheet, the region from which substorm particles appear to come. The mission is to be a cooperative effort with the Federal Republic of Germany and plans call for its start in FY 1980 and launches in 1981-2.

Two small spacecraft (55 kg each) will be involved. The *Charge Composition Explorer* is to be launched in late 1981 into an elongated equatorial orbit with apogee at 8 R_E (8 earth radii). It will carry a magnetometer and three ion detectors, capable of resolving ion masses and thus distinguishing between artificially injected species and naturally occurring ones. For the first few months in orbit CCE will monitor the naturally occurring energetic particles, setting up a data base for reference before artificially injected particles are added to the environment.

Early in 1982 the second spacecraft, the *Ion Release Module* (IRM) will be launched into an elongated orbit extending to 20 R_E and initially stretching past the magnetospheric boundary on the day side of the earth. IRM will carry three ion release canisters—two of them containing lithium and one containing europium. It will also include a magnetometer, making it possible to determine the magnetic environment at the time of the ion release and later to measure the magnetic effects of the released ion cloud.

One lithium canister will be released by IRM at 20 R_E, in the solar wind upstream of the point where it first encounters the magnetosphere. Within about one hour, sunlight will have ionized an appreciable fraction of the lithium vapor and the resulting ions will be transported—and perhaps accelerated—by ambient electromagnetic fields, through the same processes which affect natural ions in the solar wind and in the magnetosphere. CCE, orbiting closer to earth, will be able to detect ions which have entered the magnetosphere and to determine their transit times and the extent to which they have been energized.

Seven months later the IRM will have its apogee on the night side of the earth. At that time it will release its second lithium charge, in the near-earth plasma sheet, which appears to be the source region of many substorm particles. The selection of the location for the release of europium vapor will depend on results obtained with lithium ions. Europium is ionized more rapidly than lithium (though less rapidly than barium—see below) and therefore will form a more compact cloud which is easier to track optically.

The AMPTE experiment utilizes the technology of barium vapor releases, used since 1967 to produce luminous clouds for tracing ionosphere fields and winds. Barium becomes ionized in sunlight quite rapidly, before it has time to disperse very far: this is an advantage in ionospheric experiments, but not on a magnetospheric scale, where one prefers lithium with its longer ionization time. Lithium also has the additional advantage of low atomic weight, close in value to that of naturally occurring H and He, so that it can be expected to behave in the same ways as they do.

A "dress rehearsal" ion release experiment preceding AMPTE, named "Firewheel", is also being considered. It,

too, will be a cooperative effort with the Federal Republic of Germany and it will utilize a test firing of the European Ariane launch vehicle.

2 Origin of Plasmas in the Earth's Neighborhood (OPEN)

The solar wind interacts with the earth's magnetosphere in a complex way, and the energy supplied by it passes through a *complicated chain of linked processes:* flows are created near the magnetospheric boundary, particles are accelerated in the tail region, they are injected into the inner magnetosphere where storage and further acceleration may occur, electric currents are established between the magnetosphere and the ionosphere and finally, at the end of the chain, the ionosphere becomes heated and disturbed by precipitating particles and by electric currents. As was noted earlier, in order to trace the time-dependent processes which govern such linked phenomena, it is essential to conduct *simultaneous measurements at different locations* in the magnetosphere, as well as in the solar wind near it.

OPEN is a multiple-spacecraft mission designed to provide such measurements in the mid-1980s. It aims at a comprehensive, global assessment of the energy balance within the region of the magnetosphere and the near-earth solar wind, including:

- Measurement of the solar wind energy input and its transfer to the magnetosphere.

- Identification of internal energy sources within the magnetosphere.

- Investigation of the interaction of these energy sources with one another

- Investigation of the storage and dissipation of energy within the magnetosphere.

- Evaluation of the ultimate impact of these processes on the low altitude earth environment

The OPEN mission is still in its study phase, but current plans are focusing on 4 spacecraft missions (Figure VII-4). It is proposed that the project will start in 1982, launches will take place over a period of 18 months or less, beginning in 1985, and that simultaneous observations will then be conducted for at least 3 years.

The 4 proposed spacecraft are:

i. The *Interplanetary Physics Laboratory* (IPL), already described among missions investigating the Sun and the heliosphere. The IPL plays the essential role of measuring the characteristics of the solar wind and of interplanetary particles and fields which constitute the "input functions" of magnetospheric phenomena.

ii. The *Geomagnetic Tail Laboratory* (GTL), which will conduct the first thorough study of the distant geomagnetic tail beyond the moon's orbit at 60-240 R_E (earth radii), an almost unexplored region of the magnetosphere. The GTL will observe the entry and acceleration of solar wind plasma deep in the tail, where rapid earthward flows of hot plasma, observed closer to Earth inside the plasma sheet, are thought to originate. In addition, it will also determine the extent to which ionospheric plasma escapes from the magnetosphere along open magnetotail field lines.

iii. The *Polar Plasma Laboratory* (PPL), placed in an elongated polar orbit with variable apogee. The PPL will study the region above the auroral zone, where particles appear to be accelerated by voltage drops along magnetic field lines and where intense radio emissions originate. It will also be able to produce global images of the aurora as viewed from above, and from its highest altitudes it will investigate solar wind plasma entry into the polar cusps and the magnetospheric boundary regions above the Earth's poles.

iv. The *Equatorial Magnetosphere Laboratory* (EML) will move in an equatorial orbit and its distance from Earth will vary from 2 to 12 R_E, enabling it to study the plasmapause, the ring current, the inner edge of the tail's plasma sheet and the noonside magnetopause. The EML will carry sensitive equipment to analyze the composition of the plasma encountered by it and also to measure energetic particles accel-

erated along magnetic field lines by voltage drops along such lines ("parallel electric fields").

The four spacecraft will be launched from the Space Shuttle using SSUS-A upper stages and will include both hydrazine and solid rocket propulsion systems, to permit necessary station keeping and appreciable orbit changes. In addition, each spacecraft will have its own unique features:

IPL will be placed in a *"halo orbit"* around the sunward libration point, similar to that of ISEE-3. In addition to its contribution to the OPEN mission, it will also conduct independent studies of the interplanetary medium.

GTL will utilize *gravitational encounters with the moon* in order to change its orbit over a wide range of distances and inclinations. Except for a few passes by interplanetary spacecraft, the properties of the distant magnetospheric tail which it will explore have never been measured.

PPL will use its solid motor to *change its apogee* later in the mission. For part of the mission, it will be at about 12-15 R_E, studying the region in which the solar wind is most intimately coupled to the magnetosphere. For the rest of the time it will have an apogee of 3-4 R_E, enabling it to investigate particle beams accelerated along magnetic field lines (detected by earlier satellites and by sounding rockets) and to investigate the source of very intense "kilometric radiation" originating above the auroral zone. It will also carry auroral imaging instruments for synoptic viewing of particle precipitation in polar regions: the images provided by such detectors provide a "global footprint" which outlines the areas where magnetospheric energy is deposited in the upper atmosphere.

EML will be able to *distinguish injections* of energetic ions *from the solar wind* (protons and He^{++}), *ionosphere* (O^+) and the *plasmasphere* (protons and He^+), in various regions of the ring current and in the inner plasma sheet. By scanning through directions close to that of the local magnetic field ("loss cone"), the instruments of EML will also be able to observe particles accelerated by voltage drops along magnetic field lines and to study their evolution in time.
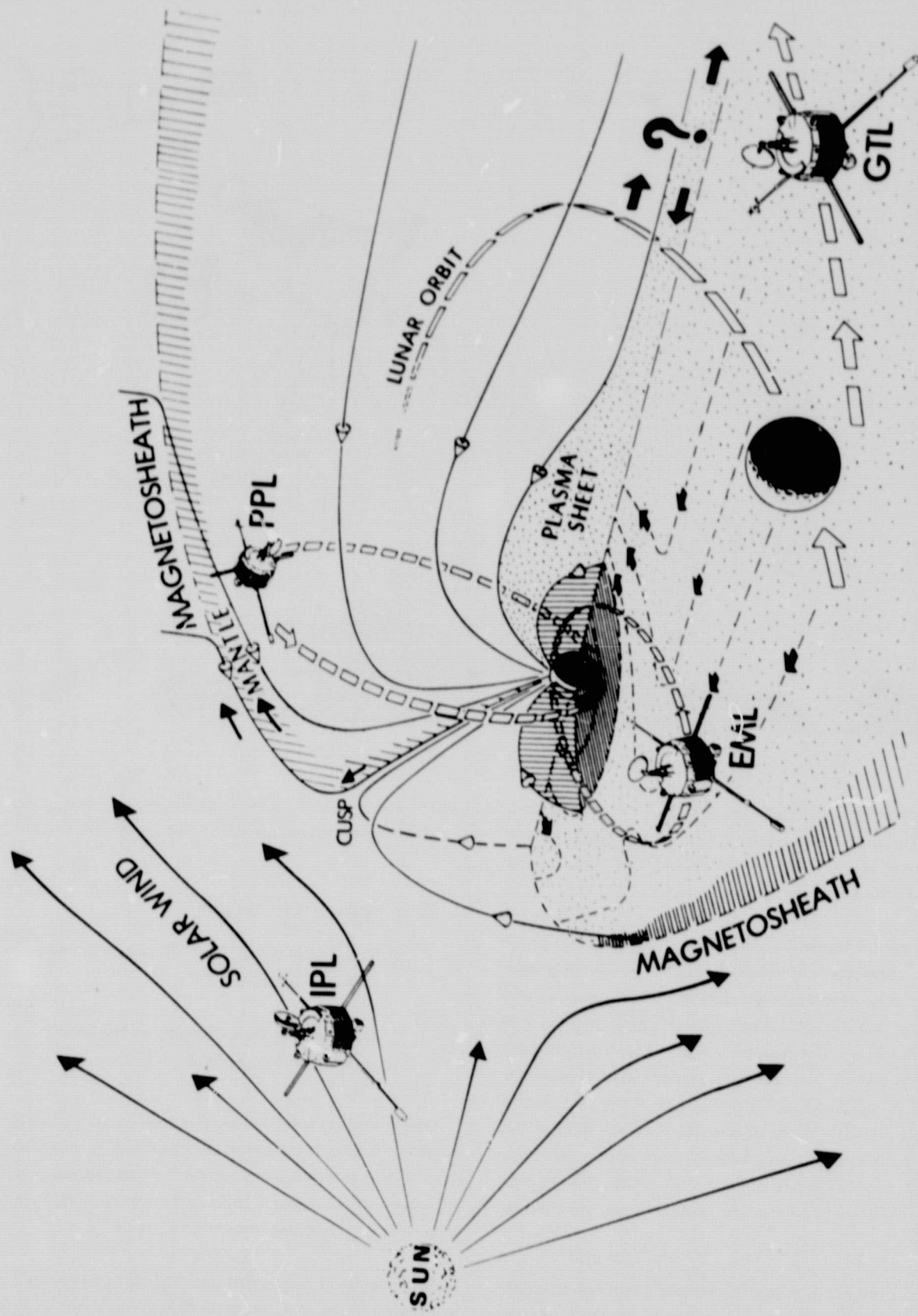
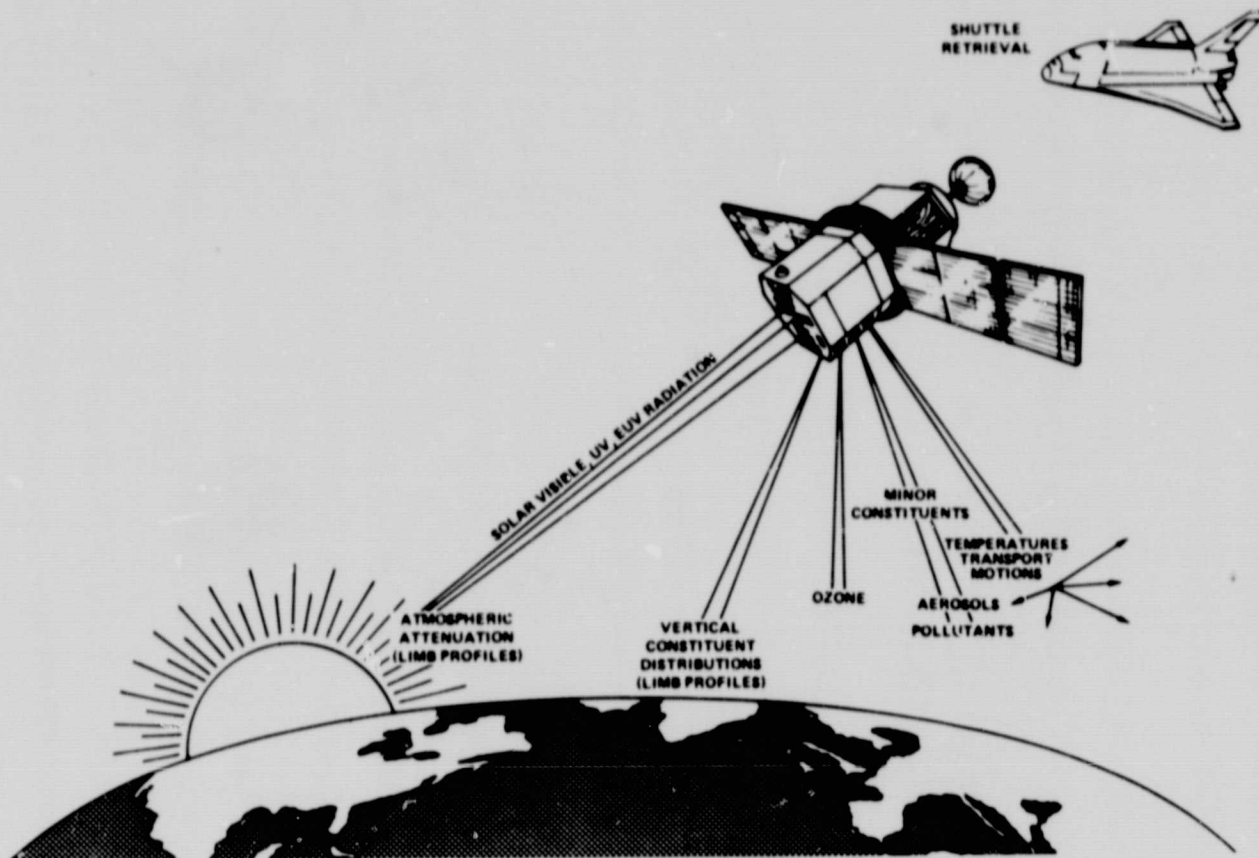Fig. VII-4 Schematic view of OPEN mission.

Fig. VII-5. Schematic view of the UARS mission.

It is expected that towards the end of the mission, EML will use its motor to move into the geomagnetic tail. There it will join GTL in mapping the fields, plasmas and motions of the distant geomagnetic field.

It has been proposed that smaller "explorer class" missions be conducted in selected regions of the magnetosphere, concurrently with OPEN. These would add supporting information about field aligned currents and electric fields in polar regions, wave and plasma processes (including recently found magnetospheric effects of 60-Hz power grid radiation) and observations of the near tail, to be correlated with those of the more distant GTL. Conversely, such missions will benefit from supporting data furnished by the OPEN mission and could complement active experiments, such as chemical releases launched by Spacelab.

Other supporting observations are expected to come from the AMPS program using Spacelab, from sensors

carried aboard UARS and from ground-based instruments such as magnetometer networks and ionospheric radars.

c. The Upper Atmosphere

1 The Upper Atmosphere Research Satellite (UARS) Program

i. Overview Remote Sensing of the Stratosphere and Mesosphere

Upper atmospheric research from space will shift its emphasis during the coming decade, from in-situ observation of the thermosphere above 120 km (stressed in the AE program) to *remote sensing of the stratosphere and mesosphere*, extending from ≈ 15 km to 85 km.

Because these layers are too high for aircraft and too low for satellites, observational data about them have been

hard to obtain. In recent years, however, there has arisen a growing awareness of the need for understanding them, because of their connection to the earth's weather and climate and also because of possible impact by man's activities on the stratospheric ozone layer. Moreover, advances in remote sensing have made it possible, for the first time, to study these altitudes extensively from space, and the Space Shuttle has made it practical to carry into orbit large and sophisticated instruments, which can be cooled down to reach the required sensitivity.

This new program is rather naturally divided into two parts. On one hand, the *Upper Atmosphere Research Satellite* (UARS) program will provide *continuous global observations* by means of relatively compact sensors together with a selected number of survey instruments. At present *two overlapping UARS missions* are contemplated, with launches in 1983 and 1984, but the hope is that this program will continue over at least one full 11-year cycle of solar activity, so that the full range of possible upper atmospheric conditions is observed.

These missions will be complemented by the *larger and more versatile instruments of Spacelab*, capable of better resolution, higher sensitivity (helped by thorough cooling of critical components) and higher data rates, but with severely limited observing time. As new techniques are tested and proved aboard Spacelab, or new needs are uncovered by its broad-band observations, the selection of instruments aboard future UARS spacecraft may be upgraded correspondingly.

The stratosphere and the mesosphere are heated by solar UV radiation: most of the energy absorption occurs in stratospheric ozone, while the temperature of the mesosphere is maintained by large-scale flows, which have only been superficially observed. In an equilibrium, of course, the rate of heating is matched by that of cooling, and *this cooling occurs primarily in the infra-red* (IR) *wavelength range*.

The IR emissions represent spectral lines and bands of the atoms, molecules, ions and radicals which produce them and they can provide considerable information about the composition and temperature of upper atmospheric layers. From space they are best observed on the limb (horizon) of the earth, since the atmosphere is then viewed tangentially (Figure VII 5) and has a relatively large depth. Typical limb observations by UARS will

measure atmospheric properties with an altitude resolution of 3 km, averaged over an area of 500 km by 1000 km. The proposed orbital altitude of 400 - 600 km is such that after the satellite views any limb region in a direction perpendicular to its orbit, it passes *above* the same region during its next orbit, at which time it can measure properties of the same region which require vertical viewing, such as cloud cover and cloud-top temperatures.

The difficulty with remote scanning of the IR emissions, especially at the longer wavelengths, is that all heated objects also emit IR, including parts of the spacecraft and the detecting instrument. Because of this, it is desirable to include *cryogenic cooling* (using liquid helium or solid hydrogen) of the instrument or at the very least of the detector. On UARS it is planned to cool key components and to preserve the cryogenic material for as long as 1.5 years by means of suitable insulation. This imposes a major limitation on the operating lifetime of UARS and has motivated studies of the possibility of using the Space Shuttle to retrieve and/or refurbish the spacecraft.

An additional method for measuring the concentrations of active minor constituents in the upper atmosphere is by solar occultation by the absorption of sunlight in selected spectral lines when the sun crosses the limb, a method also used by the Solar Mesosphere Explorer (SME) described earlier. This method can be extremely sensitive, but it may only be used twice in each orbit and even then only for a small region of the earth's limb. Like, SME, UARS is also expected to monitor solar UV emission in order to determine the energy input into the upper atmosphere and to follow its variation during times of changing solar activity.

A number of different instruments is being considered for such remote sensing, some of them still under development. Some are *radiometers*, permanently tuned to a spectral line of some selected component, while others are *spectrometers*, capable of scanning an entire spectral range: the latter class is more versatile but is also more demanding where it comes to power, weight, cooling and data transmission. Broad-band spectrometers are certainly suitable for Spacelab AMPS missions, and it is anticipated that some UARS missions will also carry at least one large instrument each. Radiometers can be designed to be sensitive to pressure and to one component of the wind velocity. A *microwave limb sounder* capable of two-dimensional wind measurements is under development, as is the

laser *heterodyne radiometer*. The latter instrument is particularly useful for measuring very low concentrations of certain species, including the man-made compounds $CFCl_3$ and CF_2Cl_2 (commercially known as Freon-11 and Freon-12) which have precipitated concern about their possible impact upon the ozone layer. Prototypes of such instruments and also of a *far-IR spectrometer* are to be test-flown on balloons in 1978-9.

ii. The First UARS Missions

UARS-A is to be launched in late 1983 from Cape Canaveral into a circular orbit with an altitude 400-600 km and an inclination 56° (the highest one available from this launch site). The launch will utilize the Space Shuttle and data will be transmitted by means of the Tracking and Data Relay Satellite System (TDRSS).

Two sample payloads have been proposed for the initial UARS missions (reference 33-2). Their main difference is that one option includes a large *cryogenic limb interferometer* spectrometer, weighing 570 kg and capable of measuring the infra-red spectra of many active species (including $CFCl_3$ and CF_2Cl_2), from which one can (among other things) derive the temperature profile of the middle atmosphere. Other proposed instruments include assorted radiometers and spectrometers, observing key properties of active minor constituents in the middle atmosphere such as ozone (O_3), CO_2, NO and H_2O. The solar UV spectrum will also be constantly monitored.

The *objectives* of the first mission are to conduct the following investigations in the middle atmosphere:

   — Study the energetics and chemistry at low, middle and moderately high latitudes, with emphasis on solar flux energy inputs.

   — Initial studies of dynamics and transport.

   — Initial studies of coupling and interactions among different processes and different atmospheric regions.

The UARS-B spacecraft will be launched by means of the Space Shuttle within less than a year. The overlap in time between the two missions will thus make it possible to compare their observations and the calibrations of their instruments.

The launch is to be from the Western Test Range, making it possible to increase the orbital inclination to 70°. Since the distance from UARS to the limb of the Earth (the horizon as viewed by its instruments) equals 23 degrees of latitude, this will enable the second spacecraft to scan the entire globe, including the *polar caps*, where it will be able to assess the upper atmospheric effects of the long polar night and polar day. Also, since most *magnetospheric inputs* of energy, momentum and particles into the upper atmosphere occur in or near the auroral zone (magnetic latitude 65° - 75°), UARS-B will be able to measure their effect on the mesosphere and stratosphere. It is expected that this spacecraft will also carry sensors such as electric field probes and particle detectors which will provide simultaneous observations of relevant magnetospheric quantities. Such sensors (aboard UARS-B or on subsequent UARS spacecraft) can lend support to the OPEN mission and conversely, OPEN can observe widespread manifestations of magnetospheric activity coinciding with energy flow from the magnetosphere into the atmosphere, as measured by UARS.

The objectives of UARS-B resemble those of the first mission, with the addition of the special points noted above, especially the effects of the polar night and day and of magnetospheric inputs.

Both UARS spacecraft will transmit about 50,000 bits/sec of data through the TDRSS satellites to a sophisticated data handling facility, developed from the successful support system of the AE mission. Processed data will be available within several days of being collected (and even more rapidly for special selected observing periods) and will be made available to all the experimenters by radio links or via the telephone network. A dedicated computer will reduce the data to standard form, prepare summary plots and data files, perform routinely a number of further derivations and will be available for computations required by experimenters.

iii. Follow-on Missions

Further UARS missions are expected to follow the initial two, probably in orbits with 70° inclination to ensure global coverage. As noted, these missions may include reflights of refurbished UARS payloads. The instrumentation will be upgraded whenever possible, especially for measurements where the early payloads only provided "minimal useful" data. The choice of new instruments

will rest on experience gained in earlier UARS missions and on new technology developed in the laboratory and tested aboard Spacelab.

The results from all UARS missions, of course, must be assimilated by theory, to provide a better understanding of upper atmospheric processes. There exist at the present time, for instance, a number of computer codes modeling the behavior of the upper atmosphere, under certain assumptions and simplifications. The observations of UARS will provide more realistic input conditions to use in such programs and will also yield data with which the predictions of such programs may be compared.

Such results will have particular significance in tracking down any processes which may cause solar activity to affect weather and climate in the lower atmosphere: several such *"Sun-weather correlations"* have been proposed (section IV-d-4), but their explanation is not clear. However, since the middle atmosphere is strongly affected by solar activity—due to both the associated enhancement of solar UV emission and the energy deposited by the polar aurora and its associated electric currents—it almost certainly acts as an intermediate link in such processes. The data furnished by UARS over the span of a solar cycle' will permit a quantitative assessment of the effects of solar activity on the stratosphere and the mesosphere and of the extent to which such effects influence the troposphere below.

In summary, the *objectives of follow-on missions* are:

- Extend the data coverage in time to permit study of upper atmospheric phenomena over a solar cycle and to evaluate year-by-year variability.

- Extend the data coverage in time to evaluate possible long-term perturbations of the upper atmosphere due to man's activities.

- As new instruments become available, to increase the accuracy, resolution and altitude coverage (e.g. for chemical species and winds) beyond the "minimum useful" level to the full extent which can be meaningfully used in theoretical models.

- Provide better temporal and spatial coverage by the use of multiple spacecraft in orbit simultaneously.

- Enhance the study of the lower thermosphere in recognition of possible coupling mechanisms with the mesosphere and stratosphere.

VIII. SPACELAB MISSIONS

a. The First Missions

The 5-year plan for Solar Terrestrial research includes two programs utilizing the Spacelab orbiting laboratory, which was already described earlier (section VI-c). These are the *Solar Observatory* program and the *Atmosphere, Magnetosphere and Plasmas in Space* (AMPS) program.

At the present time, the payloads for the first two Spacelab missions have been selected. In addition, Orbital Flight Test 5 (OFT-5) of the Space Shuttle, currently scheduled for October 1980, is also expected to carry a limited scientific payload using one of the Spacelab pallets. All these missions will carry mixed payloads, parts of which will be devoted to investigations in astronomy, life sciences and technology, but the following experiments aboard them are part of the Solar Terrestrial Program:

Orbital Flight Test 5 will include:

— A "Plasma Diagnostic Package" (PDP) subsatellite for measuring plasma properties and electromagnetic fields around the shuttle. On the OFT-5 flight the PDP will remain attached to a manipulator boom, which will be deployed into the vicinity of the Shuttle's cargo bay. On the second Spacelab flight, the same subsatellite is to be released into free flight.

— A solar X-ray polarimeter, to measure the polarization of hard X-rays from solar flares and thus provide information about the mechanism generating them.

— Instruments to observe electrical charging of the Shuttle in undisturbed flight (this is expected to be small, but could offset some on-board observations) and also the charging effects produced by the operation of a small electron accelerator. The latter test is in preparation to the more elaborate accelerator experiment on Spacelab 1.

— A solar ultraviolet spectral irradiance monitor, measuring the absolute intensity of solar UV radiation over a wide range. This instrument will provide new data for deriving the heating of the upper atmosphere and also for better modeling of the Sun's envelope.

Spacelab 1, utilizing the Spacelab cabin and one pallet (Figure VIII-1), is tentatively scheduled for the 11th flight of the Space Shuttle in mid-1981 and will carry:
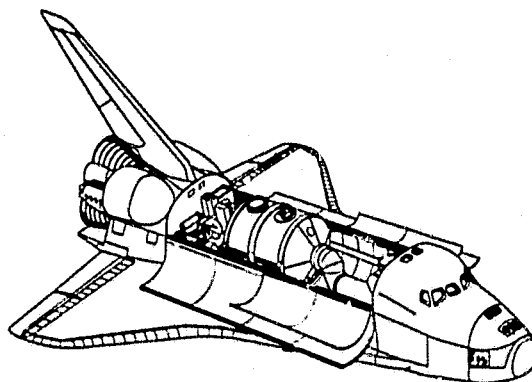

Fig. VIII-1. Spacelab 1.

65

- An array of 5 spectrometers to observe the *airglow* between 200 A and 12000 A, providing a wide range of information about the composition and energy budget of the thermosphere and about the production, loss and transport of photoelectrons.

- ATMOS, a *solar occultation spectrometer* functioning between 2 and 16μ (see section on Solar Mesosphere Explorer).

- A "grille spectrometer" operating between 2.5 and 13μ, for both solar occulation and limb emission measurements. Attached to a 30 cm telescope, this instrument has operated successfully from aircraft and balloons.

- A *Michelson interferometer* for studying *temperatures* and *winds* in the mesosphere and thermosphere, using the structure of selected spectral lines of oxygen and a spectral band of OH.

- An *electron accelerator* experiment which also includes an arcjet, radio wave receivers, particle detectors and other accessories. This will be the initial test of the accelerator facility, which is meant to become one of the major components of the AMPS program (see further on). On this flight the electric neutralization of the Shuttle during accelerator operation will be examined, as will the propagation and stability of the electron beam and the possibility of exciting artificial auroras and airglow emissions.

- A very sensitive TV camera, capable of observing both natural auroras and artificial ones (see above). Optical filters will be provided in order to produce images in narrow spectral bands and thus enhance the contrast. The camera is also sensitive to ultraviolet and by the use of filters it can be tuned to the UV lines of Mg$^+$ ions at 2795 A and 2802 A, allowing such ions to be used as tracers of ionospheric motions.

Other experiments will monitor the *solar constant* (an observation supplemented by precise measurements of the solar spectrum) and trace the magnetic and electric field structure in the upper ionosphere by relatively low level *beams of electrons and ions*.

Spacelab 2 will carry no separate cabin but only 4 pallets (Figure VIII-2) and is tentatively scheduled for the 14th flight of the Space Shuttle, in 1981. Three of its instruments will observe the Sun and they include
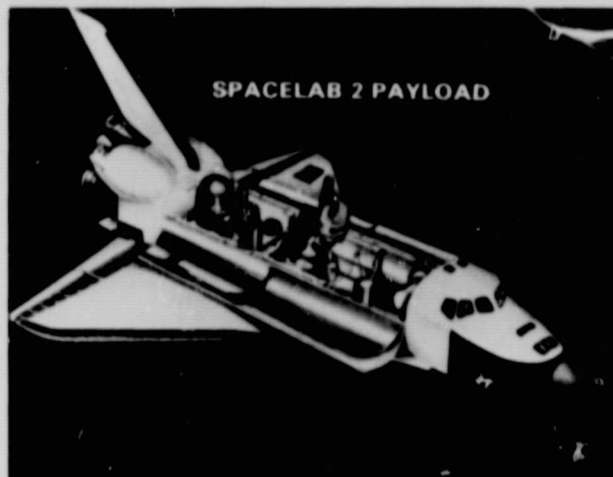

Fig. VIII-2. Spacelab 2

- A magnetograph for measurement of solar magnetic fields and flow velocities.

- A solar helium abundance experiment.

- A High Resolution Telescope and Spectrograph (HRTS), covering the UV range from 1175 A to 1715A. This instrument has successfully operated on rocket flights and it has been proposed for the initial flight of SOT (below).

Spacelab 2 will also try to produce ionospheric depletions by firing its main thrusters (see below, section on CRM) and it will eject the PDP subsatellite previously tested aboard OFT-5 for performing plasma experiments away from the Shuttle

b. Later Missions

The flight schedule following these first two missions is still flexible, but the general lines along which the programs of the Solar Observatory and AMPS will develop are guided by the development of a number of large instruments. Some of these are planned as facilities and will be shared by a number of users, some (e.g. viii. below) are "principal investigator" (PI) instruments, and some could

conceivably start out as PI instruments and be later converted to shared operation. The instruments are:

In the Solar Observatory

i. The Solar Optical Telescope (SOT).

ii. The Grazing Incidence Solar Telescope (GRIST).

iii. The Hard X-Ray Imaging Instrument (HXII).

In the AMPS program

iv. The Spacelab Lidar (Light Detection and Ranging) Facility.

v. The Cryogenic Limb Scanning Interferometer and Radiometer (CLIR).

vi. The Wave Injection Facility (WIF).

vii. The Chemical Release Module (CRM).

viii. The Spacelab Accelerator.

ix. The Subsatellite Program.

All these are expected to evolve from relatively simple first-generation experiments and gradually acquire more versatility and sophistication. Reports by scientific study teams on all the above (except for ii and viii) were presented to NASA and were reviewed in May 1978, and their main conclusions will be given in the sections that follow. Several points shared by the entire Spacelab program are worth noting here:

(1) In addition to the major instrumental efforts listed, Spacelab will carry a number of *smaller experiments*, resembling some of those listed for the first two flights—e.g., first space-tests of instruments intended for UARS (see section describing that mission) or "quick reaction" experiments for solar studies. Furthermore, some of the facilities—SOT and CRM, for instance—incorporate flexible designs which enable them to use specific-purpose equipment supplied by individual experimenters.

(2) Spacelab is an *international effort*. Not only are the basic cabin modules and their accessories provided by the European Space Agency (ESA), but many of the experiments (e.g. about half the number of those planned for the first two flights) are provided by scientists outside the US. Specifically, the GRIST telescope (see below) is being planned by ESA (though no formal agreement about its role does yet exist), the electron accelerator (to be flown aboard Spacelab 1) is provided by a team from the University of Tokyo, and there exists a strong possibility that a Canadian group will assume responsibility for the Wave Injection Facility (WIF).

(3) Most facilities will *start with relatively elementary configurations*, gradually adding components and complexity. This will not only help spread out the cost, but will also allow experience gained in early experiments to guide the design of later ones. The *subsatellite*, for instance, is to become an important accessory in many AMPS experiments, but early phases of the program will operate without it. Another accessory considered for later flight is the *tether*, a long cable extending up to 100 km from the Shuttle, possibly carrying an instrument package or a balloon at its end.

c. The Spacelab Solar Observatory

The 3 main solar instruments planned for Spacelab are designed to cover *a wide range of the Sun's electromagnetic spectrum*. In the visible and the UV, a primary aim is to resolve details far smaller than those observable from the ground, through the Earth's unsteady atmosphere. Shorter wavelengths, associated with high-energy and high-temperature processes, cannot be observed from the ground at all because of atmospheric absorption: these are expected to be especially valuable in studies of the corona and of solar flares.

1 The Solar Optical Telescope (SOT)

The SOT facility will include a *main mirror* of diameter 125 cm, usable from the infra-red down to 1100 A. At 5500 A, it will have a resolution of 0.1" (72 km at the center of the solar disk), about 3 times better than the resolution obtained under best conditions with the most powerful instruments on the ground. At the shorter wavelengths resolution improves to about 20 km, making it possible to determine extremely accurately the locations and dimensions of compact energy release regions in solar flares.

The mirror will be attached to a rigid *truss*, 7.31 meters long and 3.81 meters in diameter, covered by a thermal

shield and oriented by an Instrument Pointing System (IPS). The truss (Figure VIII-3) serves a double purpose: it can hold up to 3 independent solar instruments (such as GRIST=see below) which would be pointed towards the Sun at the same time as SOT, and it can also contain up to 6 instrument canisters which, by swinging or rotating into observing position, can take turns in using the main 125

Fig. VIII-3. The Spacelab Optical Telescope (SOT) truss, deployed in orbit.

cm mirror. The truss arrangement will also brace its instruments during landings and will contain ingenious arrangements for reflecting back unwanted parts of the solar image and thus avoiding heating problems.

The objectives of SOT include:

i. It will search for Alfvén waves with wavelengths in the range 15-150 km, invoked in order to explain the relative *coolness of sunspots.*

ii. Previously, much of the Sun's magnetic field has been observed to emanate from intensely magnetized *"magnetic knots"*, so small that they were just barely resolved by ground instruments. SOT will try to determine the magnetic structure of the photosphere on an *even smaller* scale.

iii. If solar flares occur due to the release of magnetic energy, they should be accompanied by *changes in the Sun's magnetic field*, and SOT will try to measure such changes.

iv. SOT will use UV emissions to trace regions of *flare energy release* within about 20 km.

The total SOT payload will weigh about 11 tons (the exact figure depends on the accessories used) and will utilize 3 Spacelab pallets. Its basic mission is to last 14 days, a sufficient time for solar rotation to bring every

solar feature into view, and two flights are planned each year. A payload of 3 instruments has been proposed for the first mission, tentatively set for April 1983:

- The Solar Optical Universal Polarimeter (SOUP), a solar magnetometer using a birefringent filter and combined with a UV spectrograph.

- PETRA, a high dispersion spectograph in the visible range, to be furnished by the Fraunhofer Institute of Germany.

- A UV High Resolution spectrograph, which could come from the payload of Spacelab 2.

2 The Grazing Incidence Solar Telescope (GRIST)

This telescope, under consideration by ESA, will cover the wavelength range from 100 Å to 1700 Å. At the lower end of this range conventional reflecting telescopes are no longer practical, but reflecting optics can still be used if the reflection occurs at a shallow angle, at "grazing incidence" (10^0 - 15^0 in this case).

GRIST will use a Wolter type II configuration with an effective aperture of 280 cm^2 and an angular resolution of the order of 1". Its image will be recorded electronically by an array of channel plates (sect. III-f-ii), although the use of film has also been considered. The instrument may observe flares on time scales as short as 0.1 seconds, while at the other extreme, with time exposures of the order of half an hour, it may contribute astronomical observations. Starlight below 912 Å is strongly absorbed by the galactic gas, but some of the nearest stars should still be observable in this range, providing new information about both them and the interstellar medium.

The objectives of GRIST include:

i. The investigation of the structure and properties of the solar *chromosphere*, the *corona* and the transition region between them. These can be studied by measuring absolute intensities of spectral lines, by comparing intensities of different lines emitted from the same region, from the broadening and shifts of such lines and from the variation in time and space of all of the above.

ii. The study of *solar flares* and of hot regions produced by them.

iii. The observation of *coronal features* such as bright spots, "holes" and streams.

iv. The measurement of va~ ~ion in *element abundances* in the Sun's corona

3 The Hard X-ray Imaging Instrument (HXII or "Hixie")

In the hard X-ray region (in the present case, at wavelengths below 5Å), optical methods cannot be used for focusing radiation and images · an only be obtained by the appropriate use of *absorbing materials* (see description of the pinhole satellite, which uses this principle). One way of achieving such selective absorption is by means of arrays of wires or grids, forming a pattern which ~ each point in the image plane allows radiation to arrive from only one direction and blocks out all others.

The *Hard X-ray Imaging Instrument* consists of grid optics and a large-area xenon proportional counter. Its capabilities include high angular resolution (4"), a large field of view (40'), high time resolution (0.001 sec during a large solar flare), high sensitivity and broad spectral coverage (2-80 keV) extending well into the domain of non-thermal energy release in solar flares. The instrument also has many applications in cosmic X-ray astronomy and potentially for auroral observations as well.

HXII will contain over 2000 grid structures, grouped in several arrays: some of them will observe a small selected area with a 4" resolution, while others will cover the entire sun but with coarse resolution only. The grid configuration may easily be changed between flights, and replacement of the detectors by arrays of germanium detectors could extend the instrument's range to the soft gamma-ray region. The instrument may be regarded as a follow-on to a simpler version aboard SMM and as a precursor to the Pinhole Satellite Mission, described earlier. It will weigh about 500 kg, occupy 1.2 x 1.2 x 3 meters and require a power of $\approx$ 650 w.

A one-week Spacelab observing program in 1983 will try to resolve the following questions, all related to the basic understanding of particle acceleration in non-thermal astrophysical processes:

i. Where within the structure of a solar flare does the primary particle acceleration take place?

ii. What is the relationship of the main flare energy release to the hot flare plasma?

iii. Is there coronal trapping of non-thermal electrons?

iv. What is the structure of the Crab Nebula when observed in hard X-rays?

d. The Atmosphere, Magnetosphere and Plasmas in Space (AMPS) program

1 The Lidar Facility

A Lidar (*Light Detection and Ranging*) instrument operates in the manner of the more familiar radar, but with a *pulsed laser* as its radiation source: a pulse of light is emitted and the time delay between emission and the return signal is measured, giving the distance to the object from which the radiation was reflected or scattered.

In many ways, the Spacelab forms a natural complement to the infra-red facility CLIR (see below): while the latter instrument is sensitive to complex molecules, the Lidar will be particularly useful in measuring the concentration of aerosols and dust. Aerosols produced by volcanic eruptions and by human activity increase the amount of sunlight reflected by the atmosphere before reaching ground and may promote a cooler climate: even if their concentration is too low to be detected from the ground, they may still have a significant impact. Such aerosols, as well as tenuous subvisible cirrus clouds which have a similar effect, are readily detected by the Spacelab's lidar.

Many other applications of the lidar facility have been identified. Reflections from the tops of clouds can provide valuable meteorological data, and *atmospheric humidity* can be sensed remotely with a 2 km resolution by lasers tuned to near-IR bands at 7200 Å and 9400 Å. At higher altitudes, the total atmospheric content of a large variety of molecules can be measured by the attenuation of a suitably tuned IR pulse, produced by a CO_2 laser. Total *ozone content*, for instance, should be measurable to within 3%.

At still higher altitudes, reflections from a layer of alkali atoms (especially Na) found to exist between 80 and 110 km can help trace gravity waves and other properties of the upper atmosphere. Reflections from meteoritic Mg^+ ions (80 - 250 km) and from noctilucent clouds can also be used for this purpose, and the lidar would also be extremely useful for observations of artificial chemical releases from Spacelab (see below).

Some lidar experiments have already successfully probed aerosols and humidity from the ground, and such methods will be directly adapted to Spacelab. Other uses require refinement of existing lasers and detectors. At present, the lidar facility is expected to contain Nd lasers, Nd-pumped dye lasers and CO_2 lasers, with a detecting telescope of 1 meter diameter. Frequently multipliers for the Nd lasers and other accessories will also be provided.

2 Cryogenic Limb-Scanning Interferometer and Radiometer (CLIR)

CLIR is designed for *remote sensing of the upper atmosphere* between 20 and 140 km, with a 2 km resolution, by observing thermal emissions in the infra-red (IR) range. It combines a Michelson interferometer spectrometer and a multichannel radiometer: both instruments share the same telescope of 25 cm aperture and can operate simultaneously. Supercritical helium will cool the detectors to 10° K, the optical components to 30° K and internal baffles to 115° K, increasing sensitivity 10,000 times above that of uncooled instruments. The entire assembly is to be housed in a cylinder 3 meters long and will be pointed with 4' accuracy towards the limb of the earth.

The functions of the two instruments of CLIR complement each other. *The radiometer* observes atmospheric emissions in 25 selected spectral ranges, between wavelengths of 1.5 and 25μ, on the short time scale of 0.05 seconds, during which the Shuttle's position does not change significantly. *The interferometer* can scan the entire range of 2.5 - 25μ with high resolution and can distinguish spectral details which provide a great amount of additional information about the constituents which emit them, but its long integration time of 1 - 10 sec. limits its ability to resolve small-scale features in the atmosphere.

CLIR is expected to contribute significantly to practically all the oustanding problems of upper atmospheric physics. Specifically:

i. *Chemistry*—Determine the concentrations of molecules and radicals in the upper atmosphere, including those which control the amount of atmospheric ozone, as functions of time and location.

ii. *Dynamics*--Measure temperatures in the middle atmosphere and use this information (under certain approximations) to reconstruct the circulation of the middle atmosphere, the forces driving it and seasonal temperature variations at the mesopause.

iii. *Energetics*--The emissions observed by CLIR constitute the main cooling mechanism of the upper atmosphere. Their spectral distribution therefore makes it possible to determine the flow of energy between different species of molecules and radicals and to assess the roles of various constituents in the overall energy transport process.

iv. *The Effects of Solar Activity and of the Magnetosphere*--Because CLIR will monitor the energy budget of the upper atmosphere (see iii) it will be able to assess energy inputs by X-rays and energetic particles due to solar activity, by auroral particle precipitation and by electric currents associated with the aurora.

v. *Perturbations*--Changes in the composition or in the energetics can also be observed when they are produced by other factors—by man-made pollution, by volcanic eruptions or by active experiments (electromagnetic or chemical) performed from Spacelab.

Many of these observations will constitute the first thorough survey of areas about which we still know very little. Thus CLIR will become one of the main tools of the *Middle Atmosphere Program* (MAP), scheduled to extend approximately from 1980 to 1985. As noted earlier, its observations will complement those of UARS and will guide the choice of UARS sensors.

3 The Wave Injection Facility (WIF)

The environment of Spacelab, at an altitude of 250-300 km, consists of the upper F layer of the ionosphere—a moderately dense plasma, almost completely collision-free. In many ways this environment is a *"cosmic plasma"* of the type existing in more distant regions of space, and Spacelab provides a way of studying its properties in-situ.

Such *plasma studies* are one of the aims of WIF, but not the only one: the facility will also study in detail wave modes and instabilities occurring naturally in the ionosphere and magnetosphere, such as spread-F "bubbles"

observed near the geomagnetic equator. And finally, it will attempt to perform *active modification experiments*, using its transmitters to trigger instabilities or to heat up the ionosphere.

The Wave Injection Facility is expected to make considerable use of a *subsatellite* launched from Spacelab and later retrieved by it, for two main reasons. First, even though Spacelab provides a convenient platform for generating electromagnetic signals, the detection of weak signals aboard Spacelab is likely to be hampered by local noise, which a subsatellite can avoid. Secondly, many proposed experiments require a considerable separation between transmitter and receiver. For instance, a fundamental relation in the theory of plasma waves and one which determines their propagation properties is the dependence of their wavelength on frequency—the so-called *dispersion relation*. Few observational tests of theoretically predicted dispersion relations exist, but they are readily performed by beaming a signal from WIF to a subsatellite and noting the dependence of the phase with which it arrives on the separation distance and on the frequency (the magnetic field intensity, plasma density and plasma temperature are also important factors here).

Other "passive" plasma experiments involve investigation of the transmission properties of antennas immersed in a plasma, and non-linear wave effects for instance, ways in which electrostatic wave modes which do not propagate may generate wave modes which do.

Studies of the natural environment will generally operate either in the *VLF band*, typically 50 - 20,000 Hz, or in frequencies useful for *ionospheric sounding*, typically 1 - 25 MHz. One area to be studied includes ionospheric "bubbles" of depleted ionization observed in near-equatorial regions: they appear to be caused by some type of plasma instability and they are responsible for ionospheric scintillations which degrade reception from communication satellites.

Other natural phenomena to be studied by WIF are the *sub-protonospheric wave mode*, a plasma wave type trapped in a region extending about 1000 km above the bottom of the ionosphere, *traveling ionospheric disturbances* (TIDs) which may be associated with gravity waves, and magnetospheric *ducting* observed in the propagation of whistler waves. WIF will also serve as a powerful diagnostic tool for chemical releases and for accelerator experiments (see below) which, among other tasks, may try to produce such ducting by artificial means.

Active experiments include attempts to precipitate trapped electrons of the natural radiation belt, by using strong VLF signals to induce the nonlinear cyclotron instability. Such instabilities have been successfully initiated by ground-based transmitters and they open interesting possibilities for experiments aimed at amplifying communication signals, modifying the radiation belt or heating limited ionospheric regions by dumping radiation-belt particles into them. *Ionospheric heating experiments*, which have been successfully conducted with powerful radar transmitters on the ground, can also be performed from WIF, and they are expected to yield useful information about nonlinear plasma processes.

The instrumentation required by WIF is readily available. The transmitter will be linked to a 100-meter antenna, and the frequency and duration of signals will be sequenced and controlled by an on-board computer. Although a maneuverable subsatellite will play an important role in WIF experiments, the initial operation of the facility will concentrate on experiments which do not require it.

4 Chemical Release Module (CRM)

The CRM, in common with some other facilities described here, is intended to adapt a successful existing technique so that it can be used and expanded by Spacelab. Since the 1960s, releases of Li, Na, TMA (trimethyl aluminum) and Sr from high altitude rockets have served as tracers for upper atmospheric winds. In addition, releases of barium vapor have served to trace the ionospheric electric field, since barium becomes ionized in sunlight within 20-30 seconds, and jets of barium propelled by shaped explosive charges have spread out such releases along entire magnetic field lines. The AMPTE and "Firewheel" missions (see section on AMPTE) plan to extend this technique to the study of large-scale ion entry into the magnetosphere.

CRM will be a spacecraft of flexible design, launched from the Shuttle by means of a SSUS-D or SSUS-A stage and containing a number of chemical release canisters, with a typical total weight of 2000 kg. A variety of such modules is to be launched, and on-board propulsion will allow each of them to follow a selected orbit: some planned orbits dip down to 150 km, others stay near the Shuttle's altitude or slightly above it, and still others can range to distances of up to 25 R_E. Over a typical lifetime

of 6 months, selected canisters will be released and detonated; the released material will be widely visible from the ground and it can be studied either by ground observers, from Spacelab and its subsatellite, or from independent spacecraft. The quantity of released material, while large compared to that of past rocket-borne experiments, is still small enough to preclude any lasting environmental impact.

Chemical release experiments can be divided into *tracer experiments* in which the released substance makes already existing features and processes observable, and *active experiments* in which it actually modifies the environment for a brief period. Proposed experiments include:

i. The generation of acoustic *gravity waves* in the upper atmosphere, which can then be observed by WIF or by a radar on the ground: the orbital kinetic energy of the released material will provide the initial atmospheric perturbation. A different approach would be the use of a lithium vapor trail 1000 km long to observe naturally occurring gravity waves.

ii. The study of *temporary depletions of the ionosphere*, caused by the release of appropriate substances. Such a depletion was achieved by a water dump during the launch of Skylab and will also be attempted by Spacelab 2.

iii. The *triggering of instabilities* in the radiation belt plasma by releases of cold lithium ions, an effect predicted by plasma theory.

iv. The study of the *acceleration* of Ba or Li ions by voltage drops along magnetic field lines, at altitudes of 1-2 R_E. Such accelerations have occasionally been observed in barium jets produced in sounding rocket experiments.

v. The use of released ions as tracers to study *large-scale dynamics of the Earth's magnetosphere*, as a continuation of the AMPTE investigation. Such experiments would be particularly fruitful in conjunction with the OPEN mission.

5 Accelerator Experiments

The electron accelerator experiment on Spacelab may be viewed as the creation of an *artificial auroral electron beam*, under controlled and closely observed conditions. Like their auroral counterpart the artificially accelerated electrons may produce auroral light and airglow when they strike the atmosphere, and their motion in the magnetosphere may help trace magnetic and electric fields which exist there.

But there also exist many additional questions which an accelerator experiment can help solve. Theoretical predictions and probably also the observation of intense "kilometric radiation" emitted above the auroral zone suggest that such beams may be *unstable* and may dissipate some of their energy by the generation of plasma waves. The accelerator experiment aided, perhaps, by WIF and a subsatellite may observe such processes under controlled conditions.

Evidence also exists that many discrete auroras are caused by electrons accelerated downwards by *voltage differences along magnetic field lines*. This interesting phenomenon (for which explanations are still incomplete) can be studied by directing an accelerator beam upwards into such a formation and noting whether its electrons are reflected back downwards and if so, with what energies and with what delays. The propagation of neutral plasma from an arc-jet may also be studied, and attempts may be made to produce magnetospheric ducts, similar to those guiding the propagation of natural whistler waves.

Spacelab 1 (as noted earlier) will carry the initial version of SEPAC (Space Experiments with Plasma Accelerators). It will use:

i. An *electron beam accelerator* (EBA) producing up to 2.5 amperes of 1-10 keV electrons, in pulses lasting 0.01 - 1 seconds.

ii. A magneto-plasma dynamic *arcjet* (MPD-AJ), producing 2 millisec. pulses of argon plasma, each pulse containing 2-5 kJ and $10^{19} - 10^{20}$ ion pairs.

The first task of SEPAC on Spacelab 1 will be an investigation of the buildup of electric charge on the Shuttle, caused by operation of the accelerator, and of the neutralization of such charge. After that, experiments will be performed to study beam instabilities and the creation of artificial auroras.

IX. IMPLEMENTATION

(a) Implementation Strategy

1 The Overall Plan

The preceding sections have described the major components of the 5-year plan the scientific problems, the unmanned missions, the Shuttle/Spacelab program, instruments and observations. All these fit together into a single overall plan to study the solar terrestrial environment. More specificially, the proposed missions are intended to find out:

i. How does energy flow from the solar interior into its envelope and from there out to space and to the Earth? The emissions which carry this energy include visible light, UV, X-rays, gamma rays, solar wind plasma and energetic particles from flares, and their study also requires the investigation of their variation with solar activity and with the solar cycle.

ii. How does this flow of energy control the behavior of the middle atmosphere, and how are processes in the middle atmosphere affected by solar activity and by man-made perturbations, in ways which may affect the human environment near the Earth's surface?

iii. What processes characterize "cosmic plasmas" in the Sun, heliosphere, magnetosphere and ionosphere?

The study of electrodynamic phenomena, waves, plasma instabilities and particle acceleration to high energies in such regions establishes a foundation for the understanding of astrophysical plasmas and of high-energy processes in the universe.

The missions described here constitute together a *concerted attack on these problems*. Although areas of research may be conveniently divided into Sun, heliosphere, magnetosphere and upper atmosphere, there exists a great deal of interaction and synergism between many of the missions. For example:

— SMM and SCADM will track the variation of solar energy emission in the UV and of other energetic radiations, while UARS and SME will try to observe related effects in the upper atmosphere.

— The Solar Probe will provide information both about the origin of the plasma that populates heliosphere and about the Sun's interior.

— IPL will observe interplanetary conditions near Earth and will thus provide a baseline for our interplanetary observations out of the ecliptic plane by the Solar Polar mission and in the outer solar system by Voyager.

UARS will observe magnetospheric inputs in polar regions, supplementing the observations of OPEN. In its own turn, OPEN will not only supply magnetospheric and heliospheric observations to support UARS and Solar Polar, but will also observe remote affects of active AMPS experiments, e.g. plasma injections.

Table II-1 shows the sequencing of the main missions. The complementary nature of the programs will be particularly evident in the period 1983-1987, when UARS, SOT, OPEN and the Solar Polar mission will provide an extensive data base about all parts of the Solar-Terrestrial environment.

2 Implementation of Advanced Technology

The plan will take advantage of many technological advances which have not been previously available the most conspicuous among them being the *Space Shuttle* and its Spacelab facilities. Indeed, most of the unmanned missions will be supported by Spacelab flights and will team up with them for common goals:

- UARS will be complemented by AMPS, particularly, by the CLIR and Lidar facilities.

- OPEN will be complemented by accelerator experiments, chemical releases and wave injection from AMPS.

- SMM, SCADM and other solar research programs will be complemented by SOT and by other solar instruments aboard Spacelab.

Such "teamwork" has already proved to be a great success with OSO 7 and Skylab. In that instance, the manned Skylab mission excelled in the capabilities of its instruments, but the OSO satellite covered a far longer time period. However, since the observations overlapped in time and could be compared, the detailed data on coronal holes provided by Skylab (as an example) could be used to calibrate OSO-7 and thus extract more detailed information about coronal holes from its data, which covered several years. Similar complementarity is expected to exist in all the future "teamed missions" listed above.

But this is not all. The Space Shuttle will also:

- Provide lower launch costs and higher payload capability, making feasible missions with heavy payloads such as SOT and the Pinhole Camera mission.

- Make possible retrieval and refurbishment of spacecraft such as UARS, SMM or SCADM. As the retrieval technique is perfected, the same spacecraft may be usefully flown over and over again.

Table II-1 (repeated) Office of Space Sciences Solar — Terrestrial Program FY 1980 Plan
Flight Programs

	New Start FY	Launch FY	Responsible Field Center
Solar Polar Mission	1979	1983	JPL
Spacelab Multi-use, Instrument Program	1979	1983	GSFC, LaRC, Ames
Upper Atmosphere Research Satellite (UARS)	1981	1983	GSFC
Origins of Plasma in Earth's Neighborhood (OPEN)	1982	1984	GSFC
Solar Cycle and Dynamics Mission (SCADM)	1983	1985	GSFC
Solar Probe	1983	1986	JPL
Pinhole Satellite Mission	1984	1987	MSFC
Solar Terrestrial Observatory	1984		MSFC

Make it possible to check out the operation of a spacecraft (such as SCADM) in the space environment, after launch but before it is placed in its final orbit, and if the need arises, retrieve it for further adjustments.

Other major innovations implemented in this plan involve *orbits* and *data systems*.

The *orbital versatility* of unmanned missions will be greatly enhanced by the advanced technology of onboard propulsion, which will be a standard feature on many future free-flying spacecraft. The orbital options will now include:

Lagrangian point "halo orbits" such as those of ISEE-3 and IPL, in which the spacecraft stays in interplanetary space, with its position almost held fixed relative to the Sun and Earth.

Jovian encounter maneuvers to gain speed and to change orbital planes, by amounts which would otherwise have required special techniques (next item below) or large amounts of fuel (Solar Polar and Solar Probe).

An ion propulsion engine powered by large solar panels, considered as an option for the Solar Probe. Operating at low thrust over a long period, this engine has the potential of providing a more efficient use of propellant weight than any other system in use.

Double-duty satellites for the OPEN project, which would spend a year or two in one orbit and would then shift to another one, sampling a completely different environment.

Multiple lunar encounters which can keep a satellite (in OPEN) inside the distant geomagnetic tail, even though the axis of the tail in space rotates as the Earth orbits the Sun.

Maneuverable and retrievable subsatellites, to operate from the Space Shuttle in conjunction with AMPS experiments.

Data systems will reflect the "computer revolution" which is also affecting other areas, in science and in commerce. Solid state microprocessor "chips" have already

reduced not only the cost and weight of data-handling circuitry, but also the power required by it, an important consideration aboard spacecraft. Nowadays such devices make possible preprocessing of data, redundant circuitry to safeguard against malfunction, in-flight calibration and flexible use of instruments. This technology is still evolving rapidly and some of its new capabilities (e.g. new memory devices) are expected to contribute to the missions included in the present plan.

The same technology has made possible integrated data systems with linked "smart terminals", such as those projected for UARS and OPEN. Such systems are also made necessary by the increased rate of data return (another by-product of the new technology) and they are expected to make data analysis and comparison faster and more thorough than ever. The increased data rates will be matched by the TDRSS (Tracking and Data Relay Satellite System) network, due to begin operation in the mid-1980s.

All these advances are expected to lead to a new level of understanding of the solar-terrestrial environment. Some central questions which this plan is expected to resolve are listed in chapter X, while more detailed objectives and capabilities are contained in chapters VII and VIII.

b. The Planning Process

Every component of the 5-year plan is the outgrowth of a careful study involving the scientific community, NASA and the aerospace industry. The procedure by which a new mission is developed is intended to ensure that it is scientifically sound and well integrated, technologically feasible, relevant to the general goals and outstanding needs of the solar terrestrial research program, that it can be performed at a reasonable cost, that experimental opportunities are fairly allocated and that data will be readily available and fairly used. Over the years, a definite "planning cycle" has evolved, and it is described below; the reader will appreciate that the missions described in chapter VII represent different stages of this cycle—that some of them are well advanced, while others are only in their initial stages.
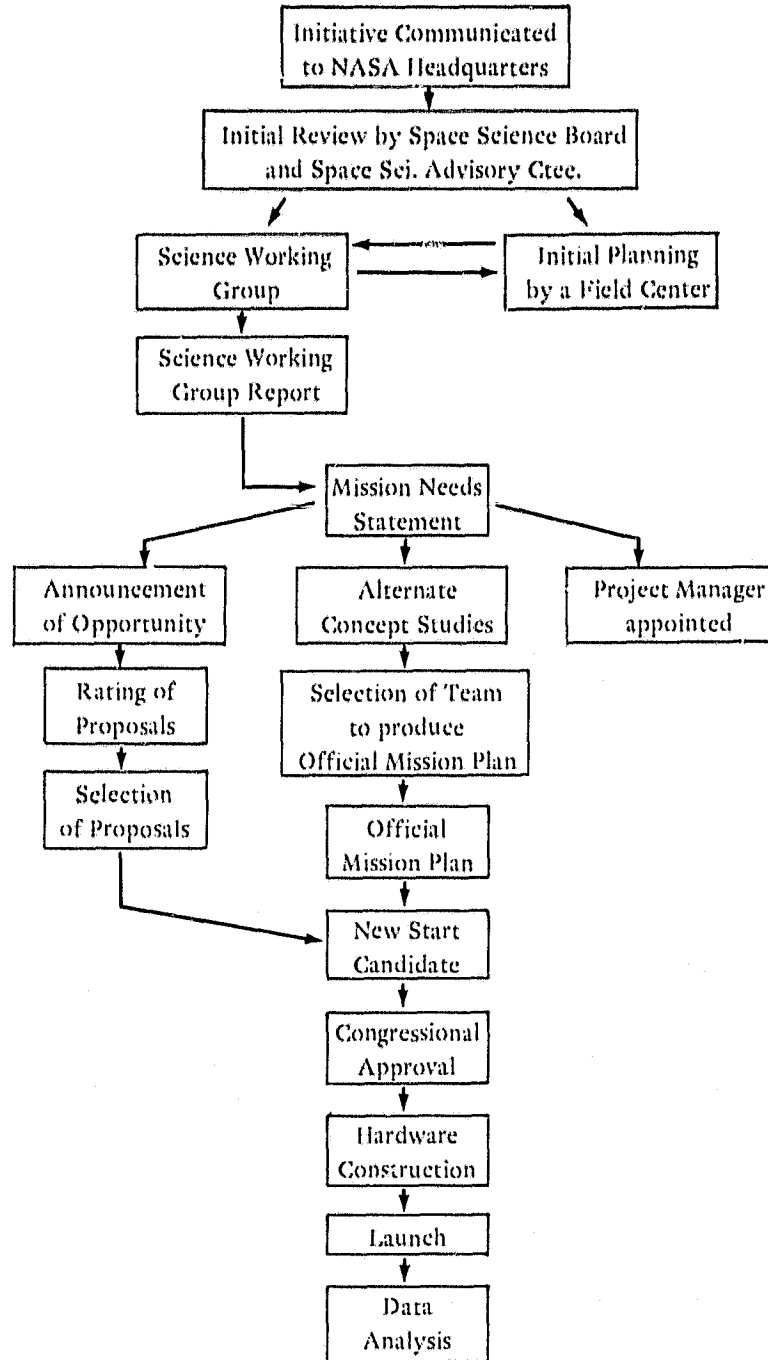
New projects may be initiated by individuals, science teams, organizations, industry labs, NASA field centers or NASA headquarters: there exists no single exclusive way.

In general, the ideas which outline a possible new project are presented in a written document which is then circulated for comment and information (Table IX-1).

NASA headquarters will next bring the proposal to the attention of advisory committees such as the Space Science Board of the National Academy of Sciences and NASA's Space Sciences Advisory Committee. If these committees express interest, the planning effort continues in a more intensive fashion. These advisory committees are continually informed and consulted about all proposed missions and other new activities of the Solar Terrestrial Program.

Table IX-1. The Planning Process

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                    ┌─────────────────────┐
                    │ Initiative Communicated │
                    │  to NASA Headquarters  │
                    └─────────────────────┘
                              │
                    ┌─────────────────────────┐
                    │ Initial Review by Space Science Board │
                    │  and Space Sci. Advisory Ctee.  │
                    └─────────────────────────┘
                         │                 │
            ┌──────────────────┐      ┌──────────────────┐
            │ Science Working  │◄─────│  Initial Planning │
            │     Group        │─────►│ by a Field Center │
            └──────────────────┘      └──────────────────┘
                    │
            ┌──────────────────┐
            │ Science Working  │
            │  Group Report    │
            └──────────────────┘
                    │
                    └──────────►┌──────────────┐
                                │ Mission Needs │
                                │  Statement    │
                                └──────────────┘
              ┌──────────────────┼──────────────────┐
    ┌──────────────┐     ┌──────────────┐     ┌──────────────┐
    │ Announcement │     │  Alternate   │     │ Project Manager │
    │ of Opportunity│     │ Concept Studies│     │  appointed    │
    └──────────────┘     └──────────────┘     └──────────────┘
           │                    │
    ┌──────────────┐     ┌──────────────┐
    │  Rating of   │     │ Selection of Team │
    │  Proposals   │     │  to produce   │
    └──────────────┘     │ Official Mission Plan │
           │             └──────────────┘
    ┌──────────────┐            │
    │  Selection   │     ┌──────────────┐
    │ of Proposals │     │  Official    │
    └──────────────┘     │ Mission Plan │
           │             └──────────────┘
           │                    │
           └──────────►┌──────────────┐
                       │  New Start   │
                       │  Candidate   │
                       └──────────────┘
                              │
                       ┌──────────────┐
                       │ Congressional │
                       │   Approval    │
                       └──────────────┘
                              │
                       ┌──────────────┐
                       │  Hardware    │
                       │ Construction │
                       └──────────────┘
                              │
                       ┌──────────────┐
                       │   Launch     │
                       └──────────────┘
                              │
                       ┌──────────────┐
                       │    Data      │
                       │  Analysis    │
                       └──────────────┘
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The initial study is primarily conducted by a scientific planning team ("science working group" or a similar title) which defines the scientific objectives and the main components of the mission. The team will also, in general, propose a sample "straw-man payload" and a tentative launch schedule. "Workshop" meetings may be held at this stage in order to discuss the mission with members of the scientific community, refine its plans and solicit wider input

At the same time NASA headquarters will request one of the agency's field centers to support this planning effort through preliminary studies and designs of the engineering aspects (for instance, of spacecraft and data systems), orbital calculations and cost estimates. Planning documents may be issued by the supporting center—some such documents are cited in the bibliography, but the reader is cautioned that they undergo frequent revision and updating.

Until recently, the planning procedure varied somewhat and centered on a "Phase A feasibility study", followed by a more detailed "Phase B design study." At present, following a directive from the Office of Management and Budget (OMB circular A-109), the second phase of the planning process for any expenditure exceeding $100,000,000 begins with the drafting of a "Mission Needs Statement" which sums up the objectives, main components and constraints of the mission. Following the signing of this statement by the NASA administrator, study teams from industry are invited to propose outlines of "Alternate Concept Studies." These studies are coordinated by a project manager and the industrial team whose outline is selected (after approximately one year) proceeds to extend its outline into a detailed study, which then becomes the official plan for the project

Some time after the "Mission Needs Statement", NASA also issues an "Announcement of Opportunity" (AO) in which scientific investigators are invited to submit proposals for experiments and bids for their construction and operation. A peer group selection committee is then chosen to rate the proposals according to their merits, after which NASA headquarters selects those proposals which it feels are most appropriate, weighing both their performance and their estimated cost.

At this point the preliminary planning is complete, but the project still lacks a commitment for financial support. The Solar Terrestrial Division now proposes the mission to

the Associate Administrator for Space Science and ultimately, to the NASA Administrator, as a tentative "new start candidate", requesting that it be funded, starting in a specific fiscal year. The NASA Administrator receives such requests in a number of fields and among them several are approved each year as "new start candidates". Their selection is negotiated with the Office of Management and Budget (OMB) and if approval follows, they are listed in the agency's proposed budget for the appropriate fiscal year.

Such items then require the approval of Congress, and their merits will generally be discussed by congressional committees as part of the process of preparing the national budget. If the "new start" is then approved, funds become available for the construction of spaceflight hardware and for the scientific instrumentation.

The above sequence is typical, but many variations exist. In smaller projects some of the phases may be shortened—"Explorer class" missions, for instance, are sometimes carried out by a single scientific group from beginning to end (SME is an example of this), and they do not require Congressional approval for specific missions. International cooperative projects may require agreements between governments, and contingencies during the construction phase may lead to modification of the mission.

The allocated funds include provisions for the analysis of initial data, and funding for further studies by prime investigators or by additional "guest investigators" is often provided afterwards by a special category of funds, described in the next section. Ultimately investigators are required to deposit their data in the National Space Science Data Center (NSSDC) or in an equivalent depository, from which it may be obtained for additional study by other qualified investigators.

The planning process for Spacelab facilities resembles in many details that of free-flying spacecraft missions. However, the use of such facilities by experimenters will follow different rules, probably resembling those which govern large shared facilities on the ground, such as telescopes and accelerators. There exist astronomical spacecraft—most recently, the "International Ultraviolet Explorer"—which have successfully operated in a shared mode, with observing time allocated to a number of different users.

The plan described in this report presents the missions, options and schedules as they appear from the middle of 1978. Like most long-range plans, it is subject to changes, yet the sequencing of its main projects is probably dictated by the related disciplines and is not likely to change drastically. Time schedules are more vulnerable: contingencies may cause delays, while opportunities (e.g. international cooperative ventures) or special needs (such as the study of the ozone layer) may advance certain selected areas. Finally, there always exists the possibility that new ideas, or newly available technology, will modify existing plans. For instance, a self-sufficient permanent orbiting observatory, supplied by the Space Shuttle, may take over many of the duties of Spacelab, over much longer periods. A preliminary version of such a *"Solar Terrestrial Observatory"* is one of the options currently undergoing preliminary study by the Solar Terrestrial Division of NASA.

c. Supporting Research and Technology

The Solar-Terrestrial Division also allocates funds for the support of a large number of relatively modest efforts, jointly known as "Supporting Research and Technology" (SRT). SRT supports activities such as theoretical studies, instrument development and solar observation from the ground.

Theoretical studies have a particular importance: often they alone can supply the ultimate end-product which motivates space missions — namely, improved understanding of the solar-terrestrial environment. To help planned missions focus on those observations which are most helpful in advancing our understanding, our theory must in every way be as advanced as our technology.

The role of theory has already been outlined in section III-7, and the Solar Terrestrial Division is currently supporting a wide range of theoretical efforts. To pursue theoretical knowledge, the division plans to set aside a separate category for support of theoretical research in solar terrestrial physics. Notable areas of theoretical work include:

i. *Plasma physics*, discussed in detail by the "Colgate Report" (reference 11-3). The Sun, the heliosphere, the magnetosphere and the upper atmosphere are all filled with plasma and manifest a multitude of distinct plasma phenomena (Table IV-1), many of them still lacking full explanation.

ii. *Computer modeling*, a technique used to an increasing degree by theorists in many diverse disciplines. Computer generated models already form a central feature in the theory of the middle atmosphere (reference 24-2, p. 192) and they are likely to continue as such and to expand in scope as more data becomes available from SME, UARS and Spacelab.

In addition, however, computer models have also been applied to other areas of solar-terrestrial physics, e.g. in reconstructing the Sun's magnetic field from surface observations, wave propagation in the Sun's interior and envelope, atomic processes in the outer solar layers, in simulating the interaction between the solar wind and the Earth's magnetosphere, in modeling the electrodynamics of the inner magnetosphere (during both quiet times and substorms) and in the study of nonlinear evolution of plasma waves and instabilities in space. The use of this theoretical tool will continue to receive encouragement and support from the Solar Terrestrial program.

Instrument development is another area which faces expansion, because Spacelab and its facilities will offer many opportunities for experiments that require from the investigators only the non-standard part of the instrumentation.

Still another class of research activities are observations from *sounding rockets*, balloons and aircraft. These are supported by a special category of funding, and will continue to be used for those investigations in which they are more effective than the use of orbiting spacecraft.

A different category of modest-size projects supported by the Solar-Terrestrial Division involves *data analysis*, beyond the operational phases of the flight missions. Several trends have increased the importance of this aspect of research, in particular:

i. The increased data output of individual missions.

ii. The rising cost of missions has led to longer intervals between them, motivating investigators to devote more time and effort to the analysis of results.

iii. The rapidly advancing capability of computer analysis techniques.

iv. Further analysis of data from completed missions, where by combining and comparing simultaneous observations from several sources, new insights and correlations are obtained.

v. The use of existing data to check new theoretical ideas and to help develop theoretical models.

A good example of the first two trends is given by the ATM solar observatory aboard Skylab: the analysis of its extensive high-resolution data has continued for years after they were collected (reference 22-6). In the future, these trends are likely to continue, especially the use of computers. The AE data system, in which a central facility handled all incoming data and was accessed by individual investigators through dedicated remote computer terminals (reference 33-5) is likely to serve as a model for the more advanced data systems of UARS and OPEN. New methods of data storage and retrieval may play an important role in such data systems and also in future developments of the National Space Science Data Center (NSSDC), which is intended to be the final depository for much of the data generated in solar-terrestrial missions.

X. AFTERWORD

When this plan is accomplished and the missions outlined here have been successfully carried out, our view of solar-terrestrial physics should become much clearer than it is now. Some important questions which currently block progress ought to be resolved, including (relevant missions in parentheses):

(1) What is the small-scale structure (50-100 km) of the solar envelope and in particular, of small-scale convective flows and their associated waves, of sunspots, active regions and flares? (Solar Optical Telescope).

(2) What takes place during a solar flare, and what changes in the Sun's magnetic field accompany the flare? (Solar Maximum Mission, Solar Optical Telescope).

(3) How constant is the solar energy output? (Solar Maximum Mission, Solar Cycle and Dynamics Mission).

(4) To what extent does the Sun's shape depart from that of a sphere an effect which might reveal whether the Sun has a rapidly rotating core? (Solar Probe).

(5) What is the composition (nuclear masses and ionization levels) of solar wind particles, how are they initially accelerated, and what are the properties of the region in which such particles originate? (ISEE-3, IPL, Solar Probe).

(6) What is the nature of the heliosphere above the Sun's poles, and how does that region differ from the heliosphere near the Earth's orbital plane? (Solar Polar Mission, IPL).

(7) What are the structure and motions of magnetospheric boundaries, and the 2-point correlations which characterize fluctuating fields in the magnetospheric tail? (ISEE 1/2)

(8) What are the electric fields and currents which accelerate particles above the Earth's polar caps and transmit energy from the solar wind to the magnetosphere? (DE, OPEN)

(9) How do particles from the solar wind and from the ionosphere become energized and confined in the ring current and tail of the magnetosphere? (AMPTE, OPEN)

(10) What governs the dynamics and chemistry of the middle atmosphere in particular, what effects do man-made pollutants have there on ozone? (UARS, CLIR, Ladar).

(11) Does the middle atmosphere serve as a link between solar activity and climate? How can solar activity perturb the middle atmosphere? (UARS, CLIR, Lidar).

(12) What electrodynamic processes both natural and artifically induced characterize the ionospheric plasma? (AMPS).

The above questions are by no means the only ones addressed by the present plan; many others were listed earlier, in the description of proposed missions. Nor should one overlook the likelihood that an extensive research program, such as the one outlined here, will uncover unexpected new data and initiate new directions of scientific inquiry. Coronal holes and fast streams in the solar wind, the "Maunder minimum" and its precursors, voltage drops along magnetospheric field lines, auroral kilometric radiation and man-made perturbations of the radiation belt (through power grid radiation) and of the ozone layer (through release of chlorofluoromethanes) all these were unexpected features added to our solar-terrestrial picture during the 1970's.

The ultimate product of all this research activity is knowledge. As author John Dos Passos wrote, after witnessing one of the Apollo launches:

"What good will it do" people ask. "Couldn't the money be better spent on earth . . .?"

The answer is not fame or fortune

The answer is not that men are impelled to the moon, like the first man to climb to the top of Everest, "Just because it is there."

The answer is not: "We do this for national glory," or to prove that some system of political economic organization works better than some other system.

The answer is that by his very nature, man has to know.

"Man has to know", and it is this knowledge which has given mankind the power to apply the forces of nature to its own benefit. The quest for such knowledge is the motivation driving all of science, including NASA's Solar-Terrestrial Program.

To enable humanity to make meaningful decisions about its environment, it needs such knowledge: we must learn to understand the processes in our upper atmosphere, the coupling between the Sun and the environment of the Earth, and the complex plasma phenomena which occur in space, on the face of the Sun and in our Earth's magnetosphere. It is hoped that the next decade in space, with the missions and programs outlined here, will add appreciably to this understanding.

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By necessity, this plan can only contain rather condensed descriptions of proposed missions and of their scientific background. Listed below are references in which additional details may be found, grouped according to their subject. Each grouping is identified by a 2-digit number and the first digit identifies the category, as follows:

  1 — Planning Documents

  2 — The Scientific Disciplines

  3 — Mission Studies

The list is meant to be representative rather than all-inclusive and will inevitably require revision and updating in the future.

Publications which are not available through regular book dealers are often difficult to obtain, and information which may be useful in this respect is therefore included with the references (note, though, that some of the older publications may no longer be stocked). Some important sources of documents are:

1. Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

2. Scientific and Technical Information Office, NASA Headquarters, Washington, DC 20546.

3. National Academy of Sciences, 2101 Constitution Ave., Washington, DC 20418.

4. National Technical Information Service (A service of the U.S. Dept. of Commerce) 5285 Port Royal Rd., Springfield, Va. 22151, tel. 703-557-4780. This source can provide microfilms of documents or hard copies produced from microfilms.

The abbreviations USGPO, STIO, NAS and NTIS will be used for the above addresses (that of NAS is sometimes preceded by the name of an originating organization within NAS, as noted in the references), and listed prices are noted wherever they are given.

For informal reports, committee chairmen or originating organizations are cited wherever possible; even if the document has been revised or replaced, such sources can often provide more recent versions, or information about the way in which they can be obtained. Additional copies of *this* report, as well as of reference 11-1, can be obtained from the Solar Terrestrial Division, Code ST, NASA Headquarters, Washington, DC 20546.

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ABBREVIATIONS AND ACRONYMS

An acronym (marked "a") is an abbreviation pronounced as a word.

A	Angstrom
AE	Atmosphere Explorer
AMPS	(a) Atmosphere, Magnetosphere and Plasmas in Space Program
AMPTE	(a) Active Magnetospheric Particle Tracer Experiment
AO	Announcement of Opportunity
ATS	Applications Technology Satellite
AU	Astronomical Unit
CCE	Charge Composition Explorer
CLIR	(a) Cryogenic Limb-Scanning Interferometer and Radiometer
CRM	Chemical Release Module
DE	Dynamics Explorer
EML	Equatorial Magnetosphere Laboratory
ESA	(a) European Space Agency
GRIST	(a) Grazing Incidence Solar Telescope
GSFC	Goddard Space Flight Center
GTL	Geomagnetic Tail Laboratory
HRTS	High Resolution Telescope and Spectrograph
HXII	(a; "Hixie") Hard X-ray Imaging Instrument
IMF	Interplanetary Magnetic Field
IMP	(a) Interplanetary Monitoring Platform
IMS	International Magnetospheric Study
IPL	Interplanetary Physics Laboratory
IR	Infra Red
IRM	Ion Release Module
ISEE	(a) International Sun-Earth Explorer
IUS	Inertial (formerly: Interim) Upper Stage

JPL	Jet Propulsion Laboratory
Lidar	(a) Light Detection and Ranging (derived from the acronym radar, generally not capitalized)
MAP	(a) Middle Atmosphere Program
MMS	Multi-Mission Modular Spacecraft
NAS	National Academy of Sciences
NASA	(a) National Aeronautics and Space Administration
NOAA	(a) National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSSDC	National Space Science Data Center
NTIS	National Technical Information Service
OFT-4	Orbital Flight Test 4
OMB	Office of Management and Budget
OPEN	(a) Origin of Plasmas in the Earth's Neighborhood
PDP	Plasma Diagnostic Package
PI	Principal Investigator
PPL	Polar Plasma Laboratory
SCADM	(a; "Scadam") Solar Cycle and Dynamics Mission
S/C	Spacecraft
SCATHA	(a) Spacecraft Charging at High Altitudes (mission)
SME	Solar Mesosphere Explorer
SMM	Solar Maximum Mission
SOT	(a) Solar Optical Telescope
SOUP	(a) Solar Optical Universal Polarimeter
SPM	Solar Polar Mission
SRT	Science, Research, Technology (funds)
SSB	Space Science Board
SSUS	(a) Spinning Solid Upper Stage
STIO	Scientific and Technical Information Office (of NASA)
STP	Solar Terrestrial Program
TDRSS	Tracking and Data Relay Satellite System
TMA	Trimethyl Aluminum
UARS	Upper Atmosphere Research Satellite
USAF	United States Air Force
USGPO	United States Government Printing Office
UV	Ultra Violet
XUV	Extreme Ultra Violet (also abbreviated as EUV)
WIF	Wave Injection Facility

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Please note: