THE STUDY OF SOLAR SYSTEM OBJECTS FROM EARTH ORBIT

A Workshop held at Goddard Space Flight Center

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Report to the Planetary Astronomy Program
Solar System Exploration Division
Office of Space Science
National Aeronautics and Space Administration
The Study of Solar System Objects from Earth Orbit
Workshop Participants

Sushil K. Atreya
University of Michigan

H. Warren Moos, Chairman
University of Colorado

William A. Baum
Lowell Observatory

David Morrison
University of Hawaii

Michael J. S. Belton
Kitt Peak National Observatory

Michael J. Mumma
NASA-Goddard Space Flight Center

Nancy W. Boggess (Observer)
NASA-Headquarters

Tobias C. Owen
SUNY at Stony Brook

William E. Brunk (Observer)
NASA-Headquarters

Carl B. Pilcher
University of Hawaii

Paul D. Feldman
The Johns Hopkins University

Gary A. Ransford (Observer)
Jet Propulsion Laboratory

Michael A. Janssen
Jet Propulsion Laboratory

A. Ian F. Stewart
University of Colorado

Gordon G. Johnson (Observer)
NASA Headquarters

Darrell F. Strobel
Naval Research Laboratory

Theodore Kostiuk, Secretary
NASA-Goddard Space Flight Center

Edward J. Weiler (Observer)
NASA Headquarters

Harold P. Larson
University of Arizona
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SUMMARY

Over the last two decades, man's understanding of the solar system has increased manyfold. The most spectacular contributions to this new knowledge have come from planetary spacecraft, from the early Explorer missions to the recent Voyager missions. In addition, significant contributions have come directly from ground-based planetary astronomy, using sophisticated techniques and instrumentation. There is, however, a third approach to the enhancement of our understanding of the solar system. An approach, although relatively unused up to now, which promises great benefits and combines features of both planetary spacecraft and ground-based observatories to gain information unobtainable by either, but complimentary to both. This approach utilizes astronomical observations from earth orbit.

It is through a combination of these three complementary approaches to solar system exploration that man's understanding and knowledge of the solar system will be maximized.

In order to assess the value of the role of planetary studies from earth orbit, a group of scientists was convened for a two-day workshop. It was concluded that observations from earth orbit represent a critical component in the overall program of solar system exploration. Observations from earth orbit will also benefit the solar system exploration probe program, by providing information to optimize the planning and design of future probes. It was also concluded that every effort should be made to fully utilize observatories developed for astrophysical observations, as solar system observations require basically the same techniques and instruments as are used for non-solar system astronomy. On the other hand, there are situations in which specialized instruments are required for specific observations of solar system objects and, in these cases, consideration should be given to the development of planetary dedicated instruments to be flown on the Space Shuttle, space platforms and free fliers.

A summary of the major recommendations is presented below. The rationale for these and additional recommendations are given in greater detail in the referenced sections of Chapter III.

(1) The Solar System Exploration Division should include, as an integral part of its program, solar system observations from earth orbit.

There are compelling scientific reasons for studying the solar system from above the Earth's atmosphere. These include global coverage, including the monitoring of dynamic phenomena in planetary atmospheres, very high spatial resolution as compared with ground-based telescopes, UV and IR observations, and extended observation time. (See III A.)

(2) A Management Operations Working Group on Solar System Astronomy from earth orbit should be formed within the Solar System Exploration Division.

A working group of planetary scientists is needed to advise and assist in the development of opportunities and instruments for planetary observations from earth orbit. (See III B.)
(3) Close cooperation should be encouraged between the Solar System Exploration Division and the Solar Terrestrial/Astrophysics Division in the planning and design of earth-orbiting observatories and related facilities in order to optimize their value for solar system observations.

Recognizing that many earth-based orbital observations of planetary objects will be made with facilities planned and operated by the Solar Terrestrial/Astrophysics Division, it is important that there be continued close cooperation between the two Divisions. Planetary scientists should be considered for membership in working groups and on scientific teams for instrumentation when appropriate. (See III C. Related recommendations are presented in III E, G, H, I, K, L and M.)

(4) Review panels for guest investigator proposals on earth-orbiting astronomical facilities and in particular the Space Telescope should include members of the planetary astronomy community.

Knowledge provided by active researchers from the planetary astronomy community is an important factor in the consideration of proposals for solar system observations by guest investigators. (See III F. See also III C and L.)

(5) The Space Telescope Institute advisory committee and supporting staff should include appropriate representation from the planetary sciences.

It is essential that persons actively working on solar system research programs serve in such positions to ensure that time on the telescope allotted for solar system research be best utilized, and to deal with the specialized operational problems associated with solar system programs. (See III F.)

(6) Specialized experiments, optimized for solar system studies from earth orbit, should be designed and developed.

Unusual spatial and spectral capabilities, not available in general purpose facilities or instruments designed for other purposes, are often required for solar system studies. (See III D.)

(7) The Solar System Exploration Division should investigate as soon as possible the utilization of the capabilities of the Shuttle for studying Comet Halley.

Although the recommendation of specific missions was not the original purpose of this Workshop, the participants felt strongly that this opportunity should be brought to the attention of NASA. (See III J.)
I. INTRODUCTION

On October 9 and 10, 1980 a group of planetary scientists was convened at Goddard Space Flight Center to examine the role of earth orbiting spacecraft in studies of solar system objects. This brief report is submitted as a description of the discussion and the conclusions of this workshop.

In addition to evaluating the types of scientific problems which can be done best from earth orbit, the workshop also examined NASA facilities in orbit and under construction, facilities in various stages of planning, and the possible need for orbital missions dedicated to planetary astronomy. These topics covered a wide range for a short meeting; however, it was felt that at this stage a broad overview was required before launching into a series of detailed studies.

The most important conclusion of the workshop was that there are compelling scientific reasons for studying the solar system from earth orbit in addition to studies by deep space missions and earth-based telescopes. These research problems stand on their own -- without the additional argument that there will be fewer deep space mission opportunities in the next decade than in the last. Section II discusses the reasons for this conclusion along with an approach to implementing an increased emphasis on planetary studies from earth orbit.

To accomplish this, the members of the workshop recommended that the Solar System Exploration Division of the Office of Space Science should increase its emphasis on research from earth orbit. A series of detailed recommendations for implementing this major recommendation are presented in Section III. The recommendations range from organizational modifications, e.g. formation of a Management and Operations Working Group for Planetary Astronomy, to recommendations with respect to specific orbital missions. The recommendations of Section III form the heart of the discussion and conclusions of this workshop.

Finally, Section IV presents for illustrative purposes a series of scientific problems which can be addressed using experiments in earth orbit. The list of subjects chosen reflects the background of the workshop participants and in no sense is all inclusive; it was the consensus of the workshop participants that a larger group with more time would have produced a much more extensive list. Despite this limitation, these examples show persuasively how observations from earth orbit can be utilized in the exploration of the solar system.
II. SCIENTIFIC APPROACH

A. Why Do Planetary Science from Earth Orbit?

The already spectacularly successful program of exploration in which NASA is engaged is revealing a solar system of great beauty, individuality and contrast. Each mission brings new discoveries of often strange and unexpected phenomena. As a consequence planetary scientists are faced with a wide range of fascinating research problems, some of which will lead to an understanding of why the solar system exists and how the earth was formed. Others bear on physical and chemical phenomena which occur within the atmospheres, on the surfaces, or even within the interiors of planets. Research on these problems will teach us how nature works in planetary environments and allow us to gain a much deeper understanding and appreciation for the similar processes that we experience directly on the earth. Planetary science is in a state of unprecedented excitement.

In order to attack these problems in the most efficient manner and with the minimum of expenditures, it is necessary to make use of the most effective research tools. Some problems require very high spatial resolution, or special observing geometries, or in situ measurements. For solving these problems we must have deep space missions. Other problems, however, require very sophisticated (and often large) equipment such as very high resolution spectrometers and very large telescopes for their solution. Still another class of problems, which as a result of the discoveries of the last ten years is now very large, requires extended time and spectral coverage. These classes of problems require facilities in earth orbit. As an example, note that telescopes in earth orbit will be able to do synoptic planetary imaging with ten times the spatial resolution of ground-based telescopes, with much longer time coverage than planetary flybys, and with much better simultaneous global coverage than most planetary orbiters. The Space Telescope CCD camera operated in the F/30 (planetary) mode could, for example, routinely record as much detail on Jupiter as in all but the near encounter Voyager images. Whenever Mars is near opposition, as another example, a small fraction of Space Telescope time could provide much better global sampling of Martian clouds and dust storms than the Viking orbiters did. Earth-orbiting telescopes offer, in fact, the most effective way of monitoring dynamic phenomena (weather) in planetary atmospheres and of doing so for the entire solar system -- our understanding of the atmosphere of the earth will be helped substantially by learning more completely how and why it differs from the atmospheres of the other planets.

B. Implementation

The workshop found that in addition to the general reasons discussed above, there were additional specific, complex -- often overlapping -- but compelling reasons for attacking a number of solar system research problems from earth orbit. The research areas discussed by the workshop during this brief meeting (presented in Sec. IV) provide illustrations of the breadth of the possible scientific research. Despite this complexity, the members of the workshop found that the scientific problems broke naturally into two groups. First, there was a large body of research which could be accomplished using the large facility class instruments developed primarily for extra solar system
research. Second, there are a significant number of important problems which cannot utilize these facilities; to attack these, specialized orbiting experiments will have to be developed by NASA.

1. Orbiting facilities

It is necessary to go into space for many reasons. These include much lower background signals, higher spatial resolution and, in many spectral regions, removal of absorption by the terrestrial atmosphere. Although these same advantages could be provided by deep space missions, for some objects and classes of problems, these properties are provided in an adequate manner by the large orbiting facilities. In addition, these facilities often carry large instruments such as those with very high spectral resolution which are not available on deep space missions. They also often provide long-term (but not fine grain) temporal coverage. Finally, we note that these orbiting facilities provide moderate throughput at intermediate cost for studying solar system objects when a deep space mission is not possible for either technical or economic reasons.

In addition to the International Ultraviolet Explorer, there are several earth-orbiting facilities in various stages of development, of which the Space Telescope and the Shuttle Infrared Telescope Facility are two of the most advanced. Because the study of solar system objects with these facilities has been presented in great detail elsewhere, we will not list possible research areas, noting that detailed discussions can be found in the STIF Working Group Report, the papers by Belton and Morrison in the Proceedings of the IAU Colloquium No. 54 Scientific Research with the Space Telescope, and the examples of Section IV.

It was clear to the workshop participants that the utilization of these facilities for planetary research will require strong cooperation between the Solar System Exploration and the Solar Terrestrial/Astrophysics Divisions. In addition, the involvement of planetary scientists in the planning and operation of these facilities should be continued and where appropriate expanded. We note that the operation of the International Ultraviolet Explorer is an exemplary example. Proposals are selected in open competition without regard to subfield. About 10% of the observing time is utilized by solar system investigations and two planetary scientists serve on the User committee. The only weakness from the point of view of planetary studies is that one or two scientists with primary research interests in this area are not members of the supporting staff to provide expertise for the unique pointing and scattered light problems associated with solar system object observations.

2. Specialized experiments

Often, special combinations of spatial and spectral capabilities optimized for solar system studies are required which are not available on the facilities planned primarily for extra solar system observations. For example, a large field of view is required for studying cometary comas and combined spectral and imaging capabilities with extreme-solar-blind detectors are needed in order to follow the Io-Jupiter magnetospheric interactions. In general, the optimization of solar system observations requires instruments with special fields of view and very low scattered light. Also, solar system studies often require
special spacecraft pointing capabilities; these include pointing close to the sun, the maintenance of a given altitude for an extended period of time, and the accurate tracking of objects that move on the celestial sphere. Planetary science has reached the point where, rather than cataloging phenomena, the emphasis is on determining the underlying causes by measurements over a wide range of planetary and solar parameters. As a result, not only are there extended time requirements, but also requirements for measurements at numerous special times; these requirements are often incompatible with the scheduling of the large general purpose observatory class facilities. Finally there are technological advances and new experimental approaches which not only must be tested, but which also provide the means of obtaining new kinds of information about the solar system.

Listed below are a few examples of major research problems which would benefit from specialized experiments.

- Halley and other comets could be studied using specially designed equipment, some of which now is in use in the sounding rocket program, flown on Spacelab and other Shuttle missions. This may be the only available way to study these objects from space when an intercept mission is not possible.

- The mechanisms of the Io-Jupiter-magnetosphere interactions and their dependence on solar and planetary parameters could be studied by measuring the extreme ultraviolet emissions from the Jovian system.

- Venus shows complex circulation dynamics in the upper and middle atmosphere. These phenomena, which were discovered by the ultraviolet spectrometer on Pioneer Venus, could be studied over an extended period from earth orbit. Similar phenomena could also be studied on Mars.

- Molecular surveys of the planets utilizing new far infrared techniques with much higher sensitivity than has been obtained previously could be made from earth orbit.

More detailed descriptions and additional examples are presented in Section IV.

The realization of planetary oriented experiments from earth orbit will require a new emphasis in the Solar System Exploration Division. In particular, the Solar System Exploration Division should evaluate the value of the space shuttle, Explorer class satellites, and space platforms for solar system science problems with special requirements that cannot be met by the large observatory class facilities. A corollary to this is that NASA should encourage and support experiments optimized for solar system studies to be flown on the shuttle and other orbiting vehicles.
III. RECOMMENDATIONS

The titles of the workshop recommendations are listed in the Table of Contents. Perhaps the most surprising fact is the large number of recommendations flowing from a meeting of only two days. This was not an accident. The members of the workshop perceived that there were many deficiencies in this area and that calls for action on many points were necessary.

By far the most important recommendation is the General Recommendation which requests that there be a new emphasis in the Solar System Exploration Division on earth orbital research. This emphasis should include a strengthened involvement with the Solar Terrestrial/Astrophysics Division in the development of large and complex, facilities in earth orbit. It should also include a detailed reassessment of the value of the Space Shuttle, freeflyers such as Explorer class satellites, and space platforms for the many important planetary science investigations that have special observing and equipment requirements that cannot be met by the missions optimized for astrophysical studies.

A. General Recommendation

We strongly recommend that the Solar System Exploration Division consider carefully the important role that observations from earth orbit will play during the 1980's in advancing planetary exploration and science. An increased emphasis on these opportunities within the Division should include close cooperation with the Solar Terrestrial/Astrophysics Division in the planning, development and operation of both individual instrument complements and major facilities for planetary observations from space. It is important that the planetary astronomy community have the opportunity to participate at all levels, in order to ensure that the special instrumentation and operational requirements of planetary investigations are accommodated. Careful consideration should be given to the development of dedicated instruments or facilities for planetary studies when the requirements of solar system exploration are not compatible with the general-purpose astronomical facilities.

B. MOWG on Solar System Astronomy from Earth Orbit

We urge the continued involvement of the Solar System Exploration Division in the development of opportunities and instruments for planetary observations from earth orbit. As a first step, we recommend the formation of a Management and Operations Working Group on solar system astronomy from earth orbit.

C. Planetary Science and Planning of Astrophysics Missions

Recognizing that many earth-orbital observations of planetary objects will be made with facilities planned and operated by the Solar Terrestrial/Astrophysics Division, we urge that the representation of the needs of solar system science be continued and improved in the planning and management of these facilities. We urge that there continue to be close consultation at NASA Headquarters between the Solar System Exploration Division and the Solar Terrestrial/Astrophysics Division, that planetary scientists be included in
all appropriate study teams and workshops, and that potential proposers (including those for single-PI facilities and Explorer class satellites) be encouraged to include planetary scientists in their science teams when the instrumentation is appropriate for solar system studies.

D. Earth Orbiting Experiments Optimized for Solar System Study

It is evident that the number of deep-space planetary missions will be small in the next decade. Rapid advances in instrumental remote-sensing capabilities have been made in recent years, and extremely important planetary studies could be made on a continuing basis were the appropriate instruments placed in earth orbit. Indeed, some studies are best done from earth orbit, notably those requiring long integration times, nearly simultaneous coverage over a hemisphere, or long-term coverage. Certain objects-of-opportunity (e.g., comets) can best be studied as a class by earth orbiting instruments (although in-situ probes of a few comets via fast-flyby or rendezvous spacecraft are essential). We recommend the funding of the definition and development of instruments optimized for solar system studies — particularly in the ultraviolet and infrared wavelength ranges — to be flown on Spacelab and other shuttle missions, on free flyers such as Explorers, and eventually on space platforms.

E. Space Telescope

We recognize and strongly support the application of the unique capabilities of Space Telescope to the study of solar system objects. Studies of the dynamics and structure of planetary atmospheres and of the dynamics and energetics of the Jovian magnetosphere are examples of investigations for which ST is particularly well suited. Additional examples are given in the Proceedings of IAU Colloquium No. 54 Scientific Research with the Space Telescope. We urge that the Solar System Exploration Division in cooperation with the Solar Terrestrial/Astrophysics Division encourage planetary scientists to utilize this facility and that they continue to explore ways in which the capabilities of this observatory can be applied to solar system studies.

F. Space Telescope Science Institute

The Space Telescope and its initial instrumentation will be among the most powerful tools available for solar system research in the next decade. Even a brief survey of the scientific problems to which it can be applied shows that we can expect a multitude of high quality proposals for extended amounts of observing time from planetary scientists. Also, previous experience with earth orbiting satellites shows that many of these observing proposals will be of considerable technical difficulty, often pushing the system close to its safety and guidance control limits. It is therefore essential that the Space Telescope Science Institute and its advisory committees, which have the prime responsibility for the selection and implementation of the scientific program, have considerable expertise in solar system research problems.

We recommend that the Office of Space Science take steps to ensure that the Institute committees set up to allocate telescope time be constituted with
representation from the widest range of astronomical interests including a representative fraction from the planetary sciences.

We also recommend that the Office of Space Science take steps to ensure that there be a representative mix of research interests in the permanent scientific staff of the Institute including some staff members who are actively working in the field of solar system research.

Positive action on these recommendations will ensure that only the highest quality and most urgent proposals for solar system research are allocated precious time on the telescope, that the capability and expertise to solve quickly operational problems associated with solar system programs will be developed within the Institute, and that there will be a growing base of data analysis software resident at the Institute suitable for the reduction and interpretation of solar system data.

G. Space Telescope Science Institute Workshop on Special Requirements for Solar System Studies

We are concerned that many planetary investigations will place special requirements on ST: for example, the need to observe targets of opportunity, the need for synoptic observations, and the pointing requirements for moving targets. We urge that the Space Telescope Science Institute, in cooperation with the Solar System Exploration Division, convene a workshop to include potential planetary observers and the appropriate STSI staff members, to consider these problems and develop solutions before the first observing requests for ST are due.

H. Space Telescope Upgrade

Concurrent with an AO for ST upgrade, we strongly recommend that NASA reassess the choice of ST focal plane instrumentation from the point of view of optimized capabilities for solar system studies. One of several areas that should be reviewed at this time is the capability for planetary IR astronomy. An ambient-temperature, earth-orbiting telescope is attractive for IR studies of planetary atmospheres, and an IR spectroscopic capability may be required on ST to complement opportunities available on other IR-oriented facilities (SIRTF, KA0, Galileo, Voyager).

I. Use of IRAS for Solar System Studies

The IRAS infrared sky survey has great potential for the study of asteroids and comets. The observations that will be made of these objects can yield compositionally sensitive albedos for most known asteroids, the determination of the size-frequency distribution of asteroids to 10 km size, discovery of new objects, particularly Apollo-Amor-Aten objects, and the investigation of the size of the nucleus and nature of the dust coma for a number of comets. We support continuing efforts to ensure that the IRAS observations of solar system bodies be identified and that adequate funds be made available to realize the potential of these data for planetary science.
J. Use of Spacelab to Study Halley's Comet

We recommend that a complement of instruments suitable for observing Halley's comet be developed and flown on Spacelab or other shuttle missions as a first step in the development of earth orbital experiments dedicated to planetary problems. We note that a similar proposal has been suggested by the Science Working Group of the International Halley Watch. This may be the only opportunity in our lifetime to plan and prepare far in advance for the study from earth orbit of a bright, active comet.

K. One Meter Class Ultraviolet Observatory

We recommend that planetary astronomers be included and encouraged to take a strong role in the definition studies of one meter class orbiting ultraviolet astronomical observatories such as the Far Ultraviolet Spectroscopic Explorer (FUSE). In particular FUSE will be of great value in support of the Galileo mission if it has the capability for observations of the Jovian magnetospheric emissions (see Sec. IV B) at the time Galileo is in orbit around Jupiter. Specific areas of concern from the standpoint of planetary observations are spectral range (extension below 912 Å to ≈500 Å), spectral resolution, spatial resolution along the slit, field of view, the use of extreme solar blind photocathodes, and the capability of tracking moving targets. Previous experience with Copernicus and IUE has shown these observatories, despite certain foreseen limitations, to be capable of making significant contributions to planetary science. It is imperative to ensure the maximum solar system capability of any facility to be built for the astronomical community as a whole.

L. Shuttle Infrared Telescope Facility

We are gratified that planetary astronomers were heavily involved in planning the SIRTF, particularly in defining its focal plane instruments. Because of the exceptional capabilities of this facility for solar system studies, it is important that planetary scientists continue to be associated with the program. We therefore recommend that (1) the AO for instruments encourage the formation of broadly based teams that will include planetary scientists, and that (2) representatives of the planetary community serve on proposal review panels. Planetary astronomers' particular requirements for synoptic coverage, high spatial and spectral resolution, and acquisition and tracking of fast moving objects may require special thought in configuring instruments and planning missions. In addition, the problem of studying faint satellites near bright planets and specific features on planetary disks or within comets may influence the design and operation of the telescope's basic control systems. Finally, we recommend that, for any SIRTF upgrade, specific attention be given by the appropriate NASA Headquarters Office to focal plane instruments and mission objectives optimized for planetary observations.
M. IR Ambient Telescope

The spectral region from 14 μm to 1 mm is significantly obscured from the ground by atmospheric attenuation. This spectral region is rich in molecular vibrational (bending modes) and rotational lines of planetary constituents. Exploitation of this region for planetary studies ultimately requires space-borne instrumentation. The SIRTF will survey most of this important spectral range at moderate resolution. Fully resolved line profiles could be obtained by the proposed IR Ambient Telescope, and these may be useful for planetary studies. We recommend that applications of the IR Ambient Telescope to planetary problems be thoroughly investigated to determine whether this facility could be an important research tool for the Planetary Program.
IV. SOLAR SYSTEM STUDIES FROM EARTH ORBIT: ILLUSTRATIVE EXAMPLES

The workshop proceeded initially by considering examples of research problems into which significant inroads could be made from earth orbit. The examples collected in this section are based on the presentations, the ensuing discussion, and contributions from workshop members. In no sense is the list of topics in the Table of Contents complete; rather, this list of sometimes overlapping examples represents the research interests of the participants; a different group of planetary scientists might come up with a slightly different list. The object of this section then is not to define, but to illustrate the kinds of exciting solar system research possible from earth orbit.

A. Comets and Other Targets of Opportunity

It has only been in the last few years that comets have been extensively studied in the vacuum ultraviolet from above the Earth's atmosphere from both sounding rockets and earth-orbiting observatories such as IUE and Copernicus. Compared with other solar system objects, comets, believed to consist of the frozen remnants of the primordial solar nebula, cannot be systematically studied by planetary probes as their time spent in the vicinity of the sun is usually measured only in weeks or months after discovery. Remote observations of comets in the ultraviolet are particularly of interest as the dominant constituent of comets, water ice, can be observed through its dissociation products, H, O and OH, all of which resonantly scatter or fluoresce strongly in the ultraviolet. Other species not detectable by ground-based techniques but seen in the UV are C, CO, C²+, S, CS and C(¹D). Recent studies of Comet Bradfield (1979) using IUE have illustrated the power of an earth-orbiting observatory, especially in its ability to track the evolution of the comet's emissions with distance from the sun in the course of the comet's traversal of the inner solar system. Missions to comets are possible only for a limited number of periodic comets whose orbits are sufficiently well-known; the simultaneous observation from earth orbit at the time of in situ measurements from a cometary encounter will provide a needed "calibration" for the earth-orbiting observatories of the "new," bright comets that appear at the rate of only one or two per decade -- but which are making their first appearance in the inner solar systems and hence are considerably more active than the short period comets. Improvements in instrumentation should greatly improve the sensitivity of future earth-orbiting observatories over that of the current generation permitting the search for and discovery of additional periodic comets present in our vicinity.

In addition to comets there are other instances of "targets of opportunity" in the solar system which would require rather rapid access to earth-orbiting observatory. Such targets might include a Martian dust storm or an magnetospheric storm at Jupiter triggered by an increase in solar activity.

B. Jupiter-Satellite Magnetospheric Interactions

The Jovian system provides a new type of planetary-magnetospheric interaction in that a large part of the trapped particles are presumed to come from the satellite Io. It is believed that the precipitation of these charged particles
and ions into the atmosphere carries enough energy to substantially alter the
temperature and abundance of both atoms and complex molecules in the upper part
of the Jovian atmosphere. Thus, an unusual situation exists in which atoms and
molecules from the small satellite Io -- possibly outgassed from the interior
by volcanic action driven by tidal deformation -- after acceleration by the
dynamo power of the rotating planetary magnetic field substantially affect the
atmosphere of Jupiter. Of course, we are not sure of this scenario -- although
it does explain many of the observed phenomena -- and many of the details are
only partially understood. In addition, the role of magnetotail particles sup-
plied by the solar wind -- the primary cause of aurora on the earth -- as well
as the role of the other Jovian satellites is not known. It is likely that
understanding this complex and fascinating set of phenomena will lead to a bet-
ter comprehension of the interaction of our own magnetosphere with the atmo-
sphere of the earth.

The Jovian magnetospheric activity manifests itself in intense emission
from the plasma torus, aurorae, and temporal variations and geographical asym-
metries (such as the equatorial atomic hydrogen bulge) in atomic and molecular
abundances. These phenomena must be studied using ultraviolet and extreme ul-
traviolet (the visible torus emissions come primarily from the cooler part of
the plasma torus), techniques which require space observatories. In addition
a long term study is required to unravel the dependences on solar activity,
the planetary magnetic field configuration, torus conditions, and gas injec-
tion rates from the satellite.

Preliminary studies with the IUE observatory and the Voyager spacecraft
have shown that the Jovian aurorae are quite variable over approximately a one
year period while the hot plasma torus appears to change only slowly. This
study has shown also that the atomic hydrogen bulge is tied to the magnetic
longitude, i.e. it is probably associated with particle precipitation, and in
addition the Ly emission from the bulge has decreased significantly over a one
year period.

A comprehensive study which will lead to a better understanding of the
important parameters in the Jupiter -- satellite-magnetosphere interaction
will require fine grained temporal studies over a long period (years), angular
resolution of 1 arc sec or better on the planet, and spectral coverage from
500 to ~1700 Å. Because the solution of this fascinating and important problem
in planetary science requires both special equipment and extensive temporal
coverage, its accomplishment may be possible only from earth orbit.

One means of accomplishing these observations is to extend the wavelength
range of the proposed Far Ultraviolet Spectroscopic Explorer downward from
900 Å to ~500 Å. Such a capability would be extremely valuable during the
Galileo mission and would supplement the UV spectrometer which will be sensi-
tive only above 1150 Å. Two uncertainties in this approach are (1) whether an
observatory class facility can permit the many observations necessary to give
the required temporal coverage, and (2) whether the field of view will be large
enough to permit detection of low abundance species in the Io torus. If it is
not possible to use an observatory class facility, a dedicated free flyer will
be required in order to make significant inroads into this pressing problem in
planetary physics.
C. Atmospheres: Molecular Constituents and Structure from UV Observations

By definition, this work can only be done from orbit, since the UV region is inaccessible from the ground. The layers of the atmosphere probed at these wavelengths overlap with those studied in the infrared, but include higher altitude regions than can be usually studied at other wavelengths. Because of the large absorption cross sections, it is often easier to detect trace quantities of many molecules in the UV than in the infrared. This advantage is especially useful in the study of species produced by photochemical reactions, since the observations refer to the same region of the atmosphere in which the reactions are taking place.

To date, progress has been hampered by limitations in spectral and spatial resolution. Nevertheless, the discovery of $C_2H_2$ on Saturn, identification of NO on Venus, $H_2$ aurora on Jupiter and Saturn, the lack of Rayleigh scattering on Titan are all significant results that are helping us understand the atmospheres of these objects.

To progress, we need the capability of a spectral resolution of $10^3$ to $10^5$ coupled with <1 arcsec spatial resolution. The spatial resolution must be real, in the sense that the entrance aperture of the spectrograph can be positioned on an object and kept at this position for the duration of the desired exposure to within the specified resolution element. Hence pointing and tracking capabilities must be adequate to permit the optical limitations of the system to define the overall performance.

With such a system, it would be possible to attack several problems that have thus far eluded both ground-based and spacecraft efforts. Among these are:

1. **Studies of colors on Jupiter** — specifically the Great Red Spot and the polar regions. Infrared observations are confused by methane, ammonia, and hydrogen vibration-rotation bands. In the near UV, these problems do not exist.

2. **Photochemistry in outer planet atmospheres.** It is necessary to understand what happens to molecules such as PH$_3$, CH$_4$, and NH$_3$ in the upper part of the atmospheres of the outer planets. At high resolution in the UV, it may be possible to detect some of the intermediate fragments as well as the beginning molecules and end products.

3. **Chemistry of the atmosphere of Venus.** Despite the series of successful probes by the U.S. and the U.S.S.R., several unanswered questions remain. To give two specific examples, the identity of a major cloud layer is undefined and the value of D/H is not known; a determination of this ratio would help in our attempts to understand the history of water vapor on this planet. Detailed study of the UV spectrum (specifically high resolution work on L$_\alpha$ in the second case) would help with both of these problems.

4. **The composition of Titan's atmosphere.** It is known from the Voyager 1 flyby that this satellite of Saturn has an atmosphere containing primarily $N_2$. The presence of a heavier gas such as argon is still a possibility. It may be possible to settle this problem from earth orbit using the FUSE facility when it is flown. Other UV studies will provide insight into the photochemical
processes in this primordial atmosphere by measurements of both molecular constituents and chemically active atoms.

(5) Spatial studies on Venus and Mars — extension to other planets. Investigations of SO$_2$ on Venus and O$_2$ on Mars will improve the understanding of atmospheric dynamics on these objects. (Venus is discussed in more detail in Subsection IV-D.) It is already known from Voyager and ground-based IR observations that there are seasonal and secular variations in C$_2$H$_6$ and C$_2$H$_2$ on Jupiter (and C$_2$H$_6$ on Saturn). These studies could be continued in the UV and probably extended to Neptune as well.

(6) Why are Uranus and Neptune different? These two planets remind us of Earth and Venus: their bulk characteristics are similar, yet their atmospheres and energy transport are very different. In particular, Neptune exhibits an upper atmosphere thermal inversion, whereas Uranus does not. The inversion is manifested by the presence of CH$_4$ and C$_2$H$_6$ in emission. On Jupiter, Saturn, and Titan, C$_2$H$_2$ is also found in an inversion region. Is it present on Neptune and/or Uranus too? If it is, what are the distributions? If it is not, what are the reasons? These are the kinds of questions one may hope to answer with UV studies of these planets.

(7) Searches for tenuous atmospheres. The detection of Rayleigh scattering indicates the presence of an atmosphere even if the gases only absorb or emit in inaccessible or poorly illuminated parts of the spectrum. A neon atmosphere on Pluto could be detected this way. Or, to say it more precisely, since CH$_4$ is detected on Pluto, a neon or nitrogen component in that atmosphere could be evaluated by measuring the UV reflectivity. A similar argument applies to Triton.

D. UV Observations of Venus and Mars

Both Venus (Pioneer Venus Orbiter) and Mars (Mariner 9) have been observed in the UV from orbiting spacecraft at spatial resolutions down to a few tens of kilometers. Both planets appear to contain real information at length scales down to these resolution limits, but both also exhibit physical phenomena containing important, even crucial, information at larger scales — hundreds to thousands of kilometers. We mention some examples before summarizing the observing needs.

(1) Venus cloudtop structure and chemistry. The Venus cloudtops show bright “polar hood” clouds extending polewards from about 60° latitude. At lower latitudes, the albedo pattern in the near UV (2000-4000 Å) is very structured with features on size scales from some tens of km up to a planetary radius, persisting for or regenerating over periods from a few hours to months or years (e.g. the "Y" feature). Associated with the albedo markings are variations in spectral absorption features due to SO$_2$ (near 2100 Å and 2800 Å) and to an as yet unidentified "other absorber" (longward of 3000 Å). The SO$_2$ is inhomogeneously mixed vertically, as are the cloud H$_2$SO$_4$ aerosols themselves; the former is revealed by the differing strengths of the two broad SO$_2$ absorptions, the latter by the varying degrees of limb-brightening and -darkening seen at different times. The chemistry, structure, and circulation at cloudtop levels and above can be usefully studied at spatial resolutions of <1000 km; convective cells are resolvable at ~100 km.
(2) Venus nightside airglow. A discovery by Pioneer Venus was the night airglow emission between 1900 and 2500 Å produced by the two-body radiative association of atoms of N and O. Because fluorescent emissions from O and CO are absent on the nightside, a local source (such as an "aurora") for the atoms is ruled out. The atoms therefore are carried from their dayside (EUV sunlight) source to the nightside by a global thermospheric circulation system. The horizontal patchiness of the night airglow therefore reflects the "turbulence" of the circulation. Pioneer Venus saw a persistent bright patch near the equator at 2 a.m. local solar time, about 6000 km across, and other, transient patches of sizes ranging down to 500-1000 km. The main patch reached a brightness of 5 kilo-Rayleighs, the transients were much dimmer; the hemispheric average zenith brightness is 800 Rayleighs. Useful observations can be made at a resolution of ~1000 km, provided that scattered light from the sunlit crescent can be eliminated.

(3) Venus dayside airglow. That the circulation responsible for the night airglow is also structured at its source on the dayside is shown by Pioneer Venus UVS images of the sunlit disc in the resonance line of atomic oxygen at 1304 Å. Variations of <30% in brightness (which averages ~5 kilo-Rayleighs) are seen over distances of hundreds and thousands of kilometers; the bright areas may be roughly circular or form long "streaks" approximately parallel to the equator. Because the line is saturated, a 30% brightness variation corresponds to a change of about a factor of two in the abundance of atomic oxygen. Smaller variations are also seen in the carbon monoxide abundance via measurements in the Fourth Positive bands (200-500 Rayleighs). Certain of these bands are of exceptional interest because they came from different altitudes in the thermosphere and can be used to determine the vertical distribution of carbon monoxide. For example, the (0,1) band at 1597 Å comes from 130-170 km; the (14,5) band at 1392 Å from ~130 km; and the (14,12) band at 1715 Å from ~110 km. (These last two are excited by an accidental resonance between the (14,0) band and solar Lyman-alpha). Thus, the vertical and horizontal aspects of the dayside thermospheric circulation can be studied in the vacuum UV at spatial scales of order 200-1000 km.

(4) Mars tropospheric ozone. The well-known 2000-3000 Å absorption in ozone permits the mapping of this gas by UV observations. The abundance of O$_3$ is controlled primarily by the abundance of water vapor, and this in turn is controlled by the tropospheric temperature which varies diurnally, geographically, seasonally, and in weather patterns from 145 K to 240 K. The purpose of mapping ozone would be to study weather patterns and seasonal changes in the troposphere, and secondarily to study the recombination of carbon dioxide via reactions catalyzed by the photolysis products of water vapor. As on earth, major weather patterns on Mars appear to exist on scales of a few thousand kilometers so that spatial resolution of order 500 km seems adequate for observing them.

(5) Mars airglow. Mariner 9 UVS measurements of the vacuum UV airglow are much less extensive and systematic than the equivalent Pioneer Venus measurements of Venus, and the emissions are fainter due to the increased heliocentric distance. Only a diurnal variation in the abundance of atomic oxygen has been established. We may surmise that measurements at ~500 km resolution would be very productive; the information available on circulation characteristics would be similar to the Venus case since the emissions and excitation
mechanisms are similar. Emissions from the nightside of Mars have not yet been observed.

(6) Hydrogen coronae. The Lyman-alpha coronae of both planets extend outwards to ~20,000 km from the surface. Gross morning/evening asymmetries on Venus are inferred from the ionospheric ion composition, but the signature of this in the corona is subdued or absent. The atomic hydrogen scale height on both planets is very large (300-1000 km), and horizontal variations in density should be similarly diffuse: observations at ~1000 km resolution would be useful.

(7) Observational requirements. In addition to the scale lengths and brightnesses mentioned above, the well-known geometrical difficulties of observing Venus and Mars must be considered. We present here a table summarizing the situations.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
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<tr>
<td>Summary of Possible Earth Orbit UV Studies of Venus and Mars</td>
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<table>
<thead>
<tr>
<th></th>
<th>λ</th>
<th>Δλ</th>
<th>ΔL</th>
<th>Brightness</th>
<th>Range (au)</th>
<th>Ang. Res. (arc sec)</th>
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<tr>
<td></td>
<td>Å</td>
<td>Å</td>
<td>km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cloudtop circulation, structure, chemistry</td>
<td>2000-3500</td>
<td>50</td>
<td>~500</td>
<td>1-10 MR/A</td>
<td>0.7-1.4</td>
<td>1.0-0.4</td>
</tr>
<tr>
<td>Night airglow</td>
<td>1900-2500</td>
<td>5</td>
<td>~1000</td>
<td>1-5 kR</td>
<td>0.3-0.7</td>
<td>4.6-2.0</td>
</tr>
<tr>
<td>Day airglow</td>
<td>1304</td>
<td>5</td>
<td>~500</td>
<td>5 kR</td>
<td>0.7-1.7</td>
<td>1.0-0.4</td>
</tr>
<tr>
<td></td>
<td>1392</td>
<td>5</td>
<td>~2000</td>
<td>200 R</td>
<td>0.7-1.7</td>
<td>4.0-1.6</td>
</tr>
<tr>
<td></td>
<td>1597</td>
<td>5</td>
<td>~2000</td>
<td>500 R</td>
<td>0.7-1.7</td>
<td>4.0-1.6</td>
</tr>
<tr>
<td></td>
<td>1715</td>
<td>5</td>
<td>~2000</td>
<td>100 R</td>
<td>0.7-1.7</td>
<td>4.0-1.6</td>
</tr>
<tr>
<td>Mars</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tropospheric ozone, weather, seasons</td>
<td>2000-3000</td>
<td>50</td>
<td>~500</td>
<td>50-500 kR/Å</td>
<td>0.4-2.4</td>
<td>1.6-0.3</td>
</tr>
<tr>
<td>Day airglow</td>
<td>1304</td>
<td>5</td>
<td>1000</td>
<td>1 kR</td>
<td>0.4-2.4</td>
<td>3.5-0.6</td>
</tr>
<tr>
<td></td>
<td>1597</td>
<td>5</td>
<td>1000</td>
<td>100 R</td>
<td>0.4-2.4</td>
<td>3.5-0.6</td>
</tr>
<tr>
<td>Hydrogen coronae: Venus</td>
<td>1216</td>
<td>5</td>
<td>1000</td>
<td>0.3-70 kR</td>
<td>0.3-1.7</td>
<td>4.6-0.8</td>
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<tr>
<td>Mars</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen coronae: Mars</td>
<td>1216</td>
<td>5</td>
<td>500</td>
<td>0.3-10 kR</td>
<td>0.4-2.4</td>
<td>1.8-0.3</td>
</tr>
</tbody>
</table>
E. Search and Discovery from Earth Orbit

Among the many observational opportunities afforded by observations of solar system objects from earth orbit is the possibility of discovering entirely new objects or phenomena. Some of these may later prove to be verifiable from the ground — just as Jupiter's rings were first found by Voyager, then detected with earth-based telescopes. However, the discoveries will be made from orbit, and in some cases this will be the only way the observations can be made.

With the increasing use of orbital facilities, many discoveries will be made by chance, just as in the case of ground-based observations. Nevertheless, there are specific things to look for; among such possibilities, one may list the following:

1) New satellites. Why doesn't Uranus have distant, irregular satellites? Probably it does, but we need to push down the magnitude limit. Pluto may also have a distant satellite. Its known close satellite will probably require the high resolution of ST before an orbit can be well determined.

2) Ring systems. Does Neptune have rings? ST can supply this information, otherwise it will be necessary to wait for several different stellar occultations before we can be sure. This could mean decades. Imaging the rings of Uranus should help define their peculiar qualities. Only an orbiting telescope can do that adequately. Additional rings of Jupiter and Saturn may also be discovered.

3) Distant Comets -- other Pluto-like planets. More information is required about comets with perihelion distances beyond 5 AU. This may require a special wide-field instrument, but initial searches could be made with ground-based Schmidt cameras. Orbiting telescopes could then determine the sizes of the larger objects and monitor their activity. Is Chiron an example? Are there "planets" beyond Pluto?

4) Planetary tori. The Io and Titan tori are now known, but nothing is known about possible similar phenomena in systems of Uranus and Neptune. Mapping Lyα and other ultraviolet emissions in the vicinity of these objects would help. This is only possible from earth orbit.

5) Volcanic activity on Mars. There are some intriguing indications of current volcanism, but no definite proof. High resolution monitoring of the visible disk may answer this important question. Although ST is unlikely to catch Martian eruptions in progress, it can probably detect telltale surface changes in known volcanic regions.

6) Dust near outer planets. Both Jupiter's ring and the E ring of Saturn appear to have been replenished over relatively short periods of time. Structures in Saturn's B and C rings may also exhibit short-term changes. Only from space will we have enough resolution to monitor these phenomena.

7) New types of asteroids. Asteroids characterized by ground-based studies are thus far predominantly found to be of two types: S and C. The ordinary chondrite meteorites -- by far the most abundant type in our collections
on Earth — are not represented. Where are the parent bodies of these objects? Perhaps they are among the small asteroids that are difficult to study from the ground. Other types of objects from the formation of the solar system may also lurk among this debris.

F. Long-Term Variations in Aeronomical Processes: UV Emissions

Many classes of planetary phenomena require observations over relatively long periods of time such as several planetary rotations, seasons, or solar cycles for understanding their physics. Provided below are two examples for purposes of illustration. The theme of these examples is far reaching and is equally valid for a host of other phenomena.

(1) Variation of Emission and Doppler Line Shape of the Jovian Lyman Alpha. Table 2 lists a number of Lyα observations made to date. One notes not only wide variations in the Lyman alpha intensity — from 0.4 kR to 14 kR — but also variations which cannot be quantitatively related to solar flux variations.

Associated with the intensity changes are also changes in the Lyα line width. The only line shape observations are those done on Copernicus satellite with a spectral resolution of 40 mA. These studies show that the line width changed by a factor of two from 60 mA to 120 mA from September 1976 to March 1978 which indicates that changes in atomic hydrogen concentration are responsible in part for the changes in the Lyα brightness.

Table 2
Jovian Lyman-Alpha Brightnesses

<table>
<thead>
<tr>
<th>Date of Observation</th>
<th>Instrument</th>
<th>Intensity (kR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971 Jan 25</td>
<td>Sounding rocket</td>
<td>4.4</td>
</tr>
<tr>
<td>1972 Sep 1</td>
<td>Sounding rocket</td>
<td>2.1</td>
</tr>
<tr>
<td>1973 May 2-3</td>
<td>Copernicus</td>
<td>0.66</td>
</tr>
<tr>
<td>1973 Dec</td>
<td>Pioneer 10</td>
<td>0.40</td>
</tr>
<tr>
<td>1976 Jan 5</td>
<td>Copernicus</td>
<td>2.8</td>
</tr>
<tr>
<td>1976 Aug-Sep</td>
<td>Copernicus</td>
<td>4.0</td>
</tr>
<tr>
<td>1978 Mar</td>
<td>Copernicus</td>
<td>8.3</td>
</tr>
<tr>
<td>1978 Dec 1</td>
<td>Sounding rocket</td>
<td>13</td>
</tr>
<tr>
<td>1978 Dec 7</td>
<td>IUE</td>
<td>11</td>
</tr>
<tr>
<td>1979 Jan</td>
<td>Voyager 1</td>
<td>14</td>
</tr>
<tr>
<td>1980 May 3</td>
<td>IUE</td>
<td>10</td>
</tr>
</tbody>
</table>
Conclusion: The aeronomical processes leading to the production of atomic hydrogen, excitation of hydrogen Lα and subsequent upper atmospheric energetics show substantial solar cycle variations. Their understanding requires instrumentation with high spectral resolution (20 mA), high spatial resolution and good pointing accuracy.

(2) Variation of H-Lα and H₂-Lyman and Werner Band Auroras on Jupiter. The IUE and Voyager observations have revealed large variations in high latitude auroras on Jupiter. Both H-Lα and H₂-Lyman and Werner band auroras have shown variations over short time periods. This variation appears to be related to the changes in the Io-plasma torus and magnetospheric processes. (See also Sec. IV B.) There are not many data to relate the observed auroral behavior to the mechanisms which may be responsible for driving them.

Conclusion: Mechanisms for auroral processes, the associated deposition of energy and the influence of the latter on the thermospheric and stratospheric chemistry and dynamics of the troposphere are not well understood. Observations of high latitude auroras over long periods of time will be required. In this case, spatial resolution is a bigger concern than spectral resolution.

The above examples can be extended to include measurements of auroras on Saturn, possibly Uranus and Neptune, and other cases such as high resolution line shape measurements of emission from the magnetospheric plasmas about planets.

G. General Atmospheric Circulation and Weather on the Planets

In comparative planetology, one important research area is the general circulation and weather on each planet. Observations necessary to characterize atmospheric motion must be made over extended periods of time to obtain seasonal time scales. They must also be much more global than the coverage planetary orbiters have thus far been designed to provide. For the particular season of Mars (southern hemisphere spring) when favorable oppositions occur, ground-based imaging has given us an intriguing sample of the global distributions and motions of clouds and the evolution of dust storms, but Space Telescope resolution is needed to provide comparable information for other seasons.

Signatures of atmospheric motion include temperature, particularly the differential temperature along constant pressure surfaces, the presence and horizontal motion of clouds, and the distributions of long-lived chemical species that serve as tracers. Remote sensing in the IR can yield the global temperature distribution in the lower and middle atmospheres of many planets. Cloud motions can be detected not only in the visible but also at higher altitudes with UV imaging, e.g. Venus. Atmospheric motions on the Earth yield a buildup of O₃, O, and He in the winter hemisphere of the stratosphere and thermosphere. Similarly on Venus atmospheric motions enhance N, O, and H in the nightside upper atmosphere and leads to the formation of NO and delta band emission. On Jupiter it is anticipated that C₂H₆ and H are tracers of atmospheric motion in the stratosphere and thermosphere, respectively. Remote sensing in the IR, UV, and visible from a spacecraft orbiting the planet in question would, of course, be more desirable in many instances. However, in
the many cases when these satellites are not available, high quality observations from earth orbiting satellites will yield good results. In addition, earth orbiters often carry specialized equipment as well as providing observations of the atmosphere over an extended period of time.

H. Surface Properties of Small Solar System Bodies

The smaller bodies of the solar system — asteroids, comets, satellites, and ring systems — can contribute greatly to our understanding of the origin and evolution of the solar system. Many of these bodies are of primitive chemical composition, preserving relatively unmodified material from the condensation of the solar nebula. Others may record the early history of chemical differentiation and numerous collisions and fragmentation that characterized the early years of the planetary system. These objects have been studied primarily by ground-based astronomical techniques, but recently a few have also been visited by spacecraft. We expect that in the future earth-orbital observations will also play an important role, together with ground-based studies and deep space probes.

The Space Telescope — or any optical system with resolution of 0.1 arcsec or better — can provide valuable imagery for a wide variety of objects that are too numerous to be explored directly by spacecraft. The larger asteroids can be imaged with \( \times 10^2 \) pixels, sufficient to determine shape and to distinguish major variations in color or albedo. Imagery of this resolution can also determine whether asteroids have satellites and, if they do, to study this surprising and interesting phenomenon. Planetary rings, with their dynamical complexity, can also be studied; at 0.1 arcsec, for instance, the remarkable azimuthal structure in the Saturn B-ring can be seen, and a definitive search can be made for a Neptune ring system. Finally, we note that it may also be possible to follow large volcanic eruptions in Io with imagery at this resolution.

Surface compositions can also be investigated for small bodies by spectral remote sensing. This work has been carried out primarily by ground-based spectrophotometry, and we expect these studies will continue. However, earth-orbital telescopes permit the extension to the ultraviolet and to regions of the infrared not accessible from the ground, thus opening the possibility of identifying new species.

I. Infrared and Sub-Millimeter Observations of Solar System Bodies

A capability for infrared/sub-millimeter spectroscopy of solar system objects must be a critical element of a well-conceived, comprehensive program for planetary studies from earth orbit. The classes of information retrieved are critically dependent on the spectral and spatial resolutions employed, and for this reason several instruments will be required. It should be noted that numerous problems require infrared/sub-mm studies for their solution, of which a few examples are given here.

The gross energy budget of a planet requires measurement of its visual (Bond albedo) and infrared radiances (self emission). It is now certain that
Jupiter and Saturn radiate more energy than they absorb from the sun, and this may be true for Neptune as well. Uranus, however, appears to be in balance, identifying it as a surprising maverick among the outer planets. It is apparently unique in having its rotation axis lying nearly in the plane-of-the-ecliptic, and this must lead to radically different circulation patterns in its atmosphere. It seems important to determine whether latitudinal differences exist in the local energy budgets of the outer planets since this will shed light on internal transport processes which are poorly understood at present. An earth-orbiting instrument of moderate spectral resolving power ($\lambda/\Delta\lambda \sim 100$) and high spatial resolution could address this problem of local balance, and provide information on interior circulation over a time scale of years, even decades. It is also needed for studying the infrared/visual spectral signatures of asteroids and cometary dust, for which this instrument could identify the spectral bands of various minerals (e.g., silicates, carbonates, ...) thus providing a way of determining their compositions and assisting in their classification.

Infrared astronomy enables us to measure the compositions and structure of planetary atmospheres and to test thermochemical equilibrium models. This interpretive framework is not only the basis of our understanding of the chemical make-up of the primitive solar nebula, but also permits the identification of non-equilibrium mechanisms that are probably responsible for many evolutionary details of planetary atmospheres. For the outer planets the relevant species are the gaseous hydrides formed from cosmically abundant elements ($H_2O$, $H_2S$, $SiH_4$, $HF$, etc.), simple gaseous hydrocarbons ($C_2H_2$, $C_2H_4$, $C_2H_6$, $HCN$, etc.), and solid compounds formed in reactions with these materials. For most detections, sensitivities must be $10^{-6}$ to $10^{-9}$ or lower, expressed as a mixing ratio with hydrogen. Observationally, this requires high spectral resolution, high sensitivity, and, increasingly, good spatial resolution. The role of earth-orbiting facilities will be to extend sensitivity and temporal limits on objects already being extensively studied (e.g. Jupiter), open up new wavelength regions for study, and permit first-time observations of those planets (e.g. Neptune) that cannot be studied from ground-based facilities. Only in this way can the observational data base be broadened to provide increasingly stringent constraints on the origin and evolution of the solar system, and on current models of planetary atmospheres.

At sufficiently high resolving power ($\lambda/\Delta\lambda \sim 10^4$) it becomes possible to measure minor constituents of planetary atmospheres, to determine the vertical temperature and pressure profiles in their tropospheres and to measure column densities of aerosols and dust. At certain wavelengths it is even possible to "see" the surface of Titan, leading to a possibility of limited imaging if sufficiently large aperture telescopes are used. For example, the infrared spectrometer on Voyager detected new molecules on Titan, and provided temperature/pressure profiles in the atmospheres of Titan, Jupiter and Saturn. An earth-orbiting cryogenic spectrometer would provide high sensitivity and comparable spatial resolving power, but with better global coverage and extended temporal coverage. Since ultraviolet and visual spectroscopy cannot provide temperature/pressure profiles and are insensitive to most polyatomic molecules, it is imperative that sensitive infrared instruments be placed in earth orbit. It should also be noted that cometary studies by infrared spectroscopy will provide critical information on the abundances of parent and daughter molecules, their excitation processes, and their fates.
A powerful argument can be made for even higher spectral resolving powers \((\lambda/\Delta \lambda \sim 10^6-10^7)\) such that true shapes of planetary spectral lines can be measured. Measurement of the line shape provides information on the local physical processes at each altitude where the line is formed. This has recently led to discovery of natural laser emission on Jupiter (NH\(_3\)) and on Mars (CO\(_2\)), and to the first direct observation of the failure of local thermodynamic equilibrium in a planetary troposphere (Mars). Furthermore, stratospheric phenomena are best studied at this resolution in the infrared and sub-millimeter, and the detection limits for trace constituents are improved dramatically at Doppler-limited resolution. Stratospheric studies will benefit immensely from observations of fully resolved rotational lines. These lines are typically stronger than those of the vibrational spectra seen at shorter wavelengths; further, the line widths are determined by pressure broadening rather than by Doppler broadening to significantly lower pressure, so that the line shape contains information on the species' distribution to higher altitudes. For example, the Doppler width at 500 \(\mu m\) is less than the pressure-broadened width in the Jovian atmosphere for pressures \(>0.2\) mbar. Hence the infrared/sub-millimeter range is of particular interest for the detection and abundance determination of the distribution of these constituents with altitude, and for the observation of parent molecules in comets.

The full development of the infrared/sub-millimeter range requires telescopes in Earth orbit because of the high opacity of the terrestrial atmosphere. Large apertures are needed to obtain sufficient spatial resolution and sensitivity for observation of the planets out to Neptune. The extension of cryogenic post-dispersed Michelson interferometry and of heterodyne receiver technology (e.g., Schottky diode mixers) in this region is required. Doppler-limited laboratory spectroscopy is also needed. Certain objectives in this spectral region are therefore long-term, and require support at this time, e.g., in the areas of sub-millimeter receiver development, studies of the construction of large antennas in space (such as the 10 meter infrared sub-millimeter telescope currently under study by the Solar Terrestrial/Astrophysics Division), and in laboratory spectroscopy. Others are near term, including implementation of the Shuttle Infrared Telescope Facility for planetary studies, implementation of certain other Shuttle/Spacelab Principal Investigator Class instruments, and ensuring that IRAS observations of planetary objects are properly processed.
APPENDIX

WORKSHOP AGENDA

October 9-10, 1980

I. SOLAR SYSTEM SCIENCE FROM EARTH ORBIT

A. Brief Presentations

  Working Group on Planetary Science: NRC Astronomy Survey Committee (Belton)

  IR Studies of Planets (Mumma)

  Comets as an Example of Targets of Opportunity (Feldman)

  UV Imaging of the CO₂ Planets (Stewart)

  Monitoring of the Jovian Aurorae (Moos)

  Unscheduled Presentations by Other Working Group Members

B. Summary Statements and Resolutions

II. FACILITIES IN ORBIT AND UNDER CONSTRUCTION

A. Hardware Review

   IUE

   Space Telescope

       Wide Field/Planetary Camera
       Faint Object Camera
       Faint Object Spectrograph
       High Resolution Spectrograph
       High Speed Photometer
       Pointing

   IRAS

   SIRTF

B. Summary Statements and Resolutions
III. FACILITIES IN VARIOUS STAGES OF PLANNING

A. Possible Facilities

Far UV Spectroscopy Experiment
ST Institute
ST Second Generation Instruments
STARLAB
Spacelab Ultraviolet Telescope
Spacelab Ultraviolet Imaging Telescope
IR Ambient Telescope
AXAF
Others

B. Recommendations

IV. ORBITAL MISSIONS DEDICATED TO PLANETARY ASTRONOMY

A. Possible Missions

Spacelab
Planetary Explorers (simple experiments emphasizing one or two spectral ranges)
Planetary Observatory (large diffraction limited telescope with multiple focal plane instruments)
Planetary Facility (telescope flown first on Shuttle and then on Space Platform, focal plane instruments changed by astronaut sortie)

V. SUMMARY