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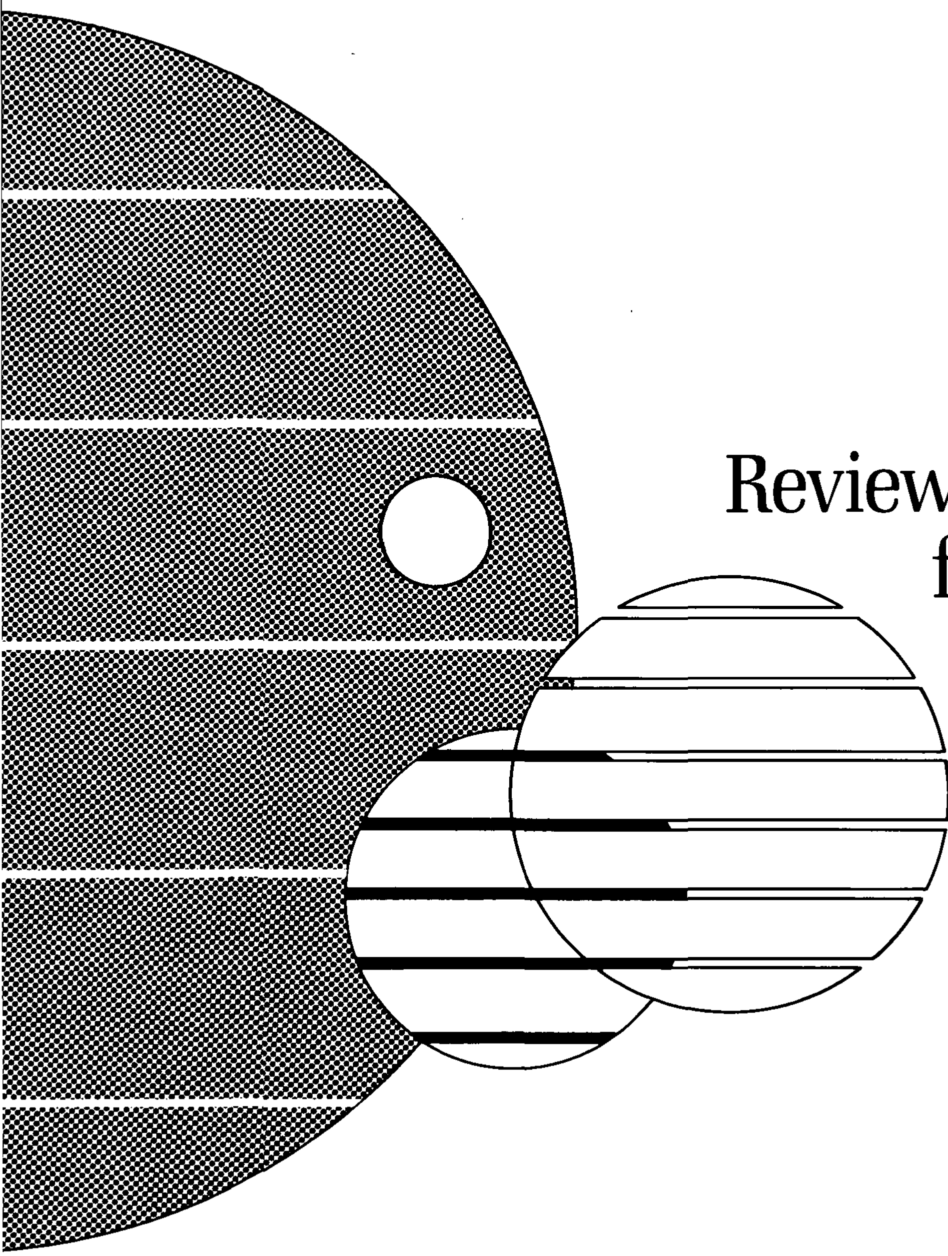
Reflectance Spectroscopy in Planetary Science

Review and Strategy for the Future



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Reflectance Spectroscopy in Planetary Science

Review and Strategy for the Future

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Preface

Reflectance spectroscopy is one of several remote sensing techniques used to study the surfaces and atmospheres of solar system objects. It has become one of the most important techniques because it provides first-order information on the presence and amounts of certain ions, molecules, and minerals on a surface or in an atmosphere. This sort of information is critical to (1) develop models of the chemical and thermodynamic history of the interior of a solid body by determining the present exposures of primary materials or their weathering products; (2) determine the processes altering the material by studying the weathering products; and (3) determine the spatial distribution of rock types and minerals on the surface and make better geologic maps. The technique can be contrasted with and is complementary to the technique of monochromatic imaging, which is used to determine the morphology of a surface, using landforms as indicators of processes which formed and altered the object.

In light of the extensive planned use of reflectance spectroscopy on most current and future solar system exploration spacecraft missions and the resulting heavy demands which will be placed on the reflectance spectroscopy community, there is a need to assess current capabilities, facilities, and personnel and the focuses and directions of current efforts. Also, the field has developed considerably over the past 15 years without a formal review by its members. Finally, in the current climate of decreasing research budgets, it is important to review the field, state the recognized important future directions and needs, and restate goals and objectives.

A workshop was held and this report written under the sponsorship of the NASA Office of Space Science and Applications Planetary Geology and Geophysics Program. A major effort was made during the 3-day workshop held April 9-11, 1986, in Yountville, California. A wide spectrum of investigators active in the field was invited, and most attended. Many of those who could not attend contributed written material and reviews of the report drafts.

Written material generated at the workshop was consolidated by the chapter leaders and the workshop chairman within a few weeks after the workshop. The chairman edited this material and his own notes into a first draft of the report, which was circulated among the participants for extensive review. The results of this review were used by the chairman to prepare a second draft. In August this second draft was circulated more widely throughout the community, including the office of the NASA sponsor. The final report was prepared in October 1986 by the chairman from the responses to the second draft. Almost all the recommendations of the participants were included in the report, reflecting the wide agreement within the community.

This report is intended as a start rather than the completion of a review of the field. NASA's need of information for programmatic reasons at this time dictated a hasty and therefore incomplete response. One of the major recommendations is that a further assessment and a revision of this document be made within 2 years.

The near-complete participation and the high level of enthusiasm exhibited by the community for this endeavor are strong indicators of the vigor and health of the field. Members of the community are in agreement on many of the issues and are anxious to work together to explore the solar system.

Acknowledgment

The efforts of Zeny Cocson and her staff are greatly appreciated.

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Chapter 1

Summary and Key Findings

Origin and Purpose of this Report

The field of reflectance spectroscopy as a remote sensing tool applied to the study of solar system objects has blossomed in the past 15 years, resulting in major discoveries about almost all solar system objects. **Reflectance spectroscopy has become one of the most important investigations on most current and planned NASA Solar System Exploration Program space missions.** The reflectance spectroscopy effort encompasses virtually all objects in the solar system, and it involves many disciplines other than spectroscopy, such as geology, geochemistry, geophysics, and atmospheric sciences. This development has depended on and resulted in increased activity in this area within the NASA basic research and data analysis program. Tight restriction of funds for the program has created hardship within the field, and the growth of the field has affected other disciplines. Yet the new mission investigations require major support from this field and NASA, and the research field must plan for this need. This report is the product of a three-day workshop held in April 1986.

Key Findings

Reflectance spectroscopy has proven to be the most powerful technique for determining surface lithologic composition by remote sensing.

The U.S. solar system exploration program will place even greater demands on the reflectance spectroscopy field than it has in the past.

There presently exists an appalling mismatch between the objectives of NASA (and foreign) planetary missions to conduct high data rate reflectance spectroscopy experiments and the present capabilites for data handling, analysis, and interpretation.

The existing reflectance spectroscopy effort is highly leveraged and vulnerable to changes in outside programs and institutions.

Communications are not sufficient.

creators of basic knowledge (e.g. surface mineralogy)↔users (e.g. volcanologists)

spacecraft projects/investigations↔basic research community

planetary program↔terrestrial remote sensing program

research/projects↔NASA Headquarters management

Description of the Field

Reflectance spectroscopy in the NASA Solar System Exploration Program is the measurement and interpretation of solar flux passively scattered from the surfaces and atmospheres of solar system objects. The wavelength range covers the near ultraviolet to the mid-infrared, approximately 0.2 μ to 5.0 μ. The spectral features sought are absorptions due to photon-induced electronic and molecular energy transitions within the surface minerals and the atmospheric particles and gases. Mineral and gas species and their abundances can often be identified from these spectral features.

The successful application of reflectance spectroscopy requires serious and interactive effort in each of several distinct and equally important areas:

Development and maintenance of laboratory, telescopic, flight instrumentation, data processing software and related personnel and facilities

Measurement of planetary reflectance spectra using ground-based, Earth-orbital and deep space probes

Laboratory measurement of spectra and related study of the properties of materials

Development of theory and models of reflectance and scattering and interpretation techniques and methods

Design of planetary investigations and interpretation of the resulting data with focus on well-defined scientific problems

Reflectance spectroscopy has proven to be the most powerful technique for determining surface lithologic and thick atmospheric compositions by remote sensing. From Mercury to Pluto, almost everything known about surface mineralogy (except for Earth and the Moon, for which we have direct documented samples, and for indirect inferences from morphology) has resulted from reflectance spectroscopy, using ground-based telescopes. A long list of scientific contributions is given in this report (chapter 3). These include mapping of high titanium minerals on the lunar maria and discovery of olivine-rich rock in some central peaks derived from depth, basalt rocks on Vesta, ice as the major constituent on most outer solar system satellites, sulfur as a major mineral involved in the volcanism on Io, iron oxide and clay minerals on Mars, and the fact that meteoritic mineral assemblages are similar to those composing most asteriods. There is groundtruth confirmation of enough of the remote measurements to lend credibility to the technique. These include lunar samples returned from areas measured remotely and meteoritic materials from asteroids.

This report contains a summary of current capabilities for deriving scientifically useful information for solar systems studies using reflectance spectroscopy techniques (chapter 4). The basic measurement objectives of the technique are:

Identify the presence of specific minerals and gases and map their distribution.

Determine the abundance of minerals present.

Estimate the composition of the individual minerals.

For minerals with strong, well-defined absorption bands (e.g., pyroxene, olivine, water ice), it is possible to detect their presence as only a few percent of the surface material and to estimate their abundance and individual key element compositions to 5 or 10%. Other minerals with no absorption bands (e.g., carbon) can be detected only by inference.

A summary of the facilities and personnel involved in spectral reflectance work under the NASA program is provided in chapter 4. The three closely related data acquisition and analysis activities are

Obtain reflectance data for planetary surfaces through a well-planned data acquisition program (ground-based and Earth-orbital telescopes and deep space probes).

Establish a solid foundation of laboratory reflectance spectroscopy measurements for materials and conditions appropriate for the surfaces studied.

Develop accurate theoretical and applied analysis capabilities to interpret the data and extract the desired information.

Reflectance spectroscopy is a technique, and it is measurement oriented. Measurement, however, is not an end itself but rather a means to answer a scientific question. **It is extremely important that the development and application of reflectance spectroscopy as a technique be motivated by basic scientific questions about the solar system and the objects and material concerning it.** This is the case for almost all the investigators' programs, for review committees are extremely sensitive to this issue and funding is so restricted. On the other hand, no one investigator can be equally active and competent in all areas of investigation required for the development and application of a technique. **Thus, the field should be reviewed overall for its balance of technique and science, and individual investigators should be allowed to emphasize areas of specialty as long as there is communication among investigators and the field as a whole is in balance.** Consortia are a good device for helping technique-oriented investigators focus on scientific problems and for keeping theoretical scientists within the reality of the data and using the best observational and modeling capabilities.

There are about 18 university, NASA center, and U.S. Geological Survey locations at which at least one investigator is active in reflectance spectroscopy as applied to planetary studies. About half these programs have only one investigator; the total number of investigators is about 30. Most investigators do not spend full time on planetary reflectance spectroscopy, and some are not funded at all by the NASA program. There is very little overlap among investigators and institution programs. **This indicates a rather thin spread of research personnel** with the associated risk of too little communication.

Essentially all the existing reflectance spectra for planetary objects have been obtained using ground-based telescopes. No U.S. spacecraft has carried a reflectance spectrometer to a planetary object. The IUE Earth-orbital telescope has been used for ultraviolet observations of asteroids, comets, and Galilean satellites. The Space Telescope instrumentation will allow observations in the ultraviolet and visible spectra.

Laboratory measurement and models of reflectance properties of materials are essential for developing the methods, background information, and the models to interpret planetary data. Laboratory measurements should concentrate on well-documented samples and on end-member materials and mixtures. Models should be developed and used to extend the laboratory measurements to the general case of different mixtures, geometries, and other conditions to avoid massive measurement projects and to respond quickly to a new planetary measurement. At least 13 research centers have laboratory reflectance spectroscopic measurement capability, and at least 6 of these have only one investigator active in this work. Yet there is very little overlap in the work at these centers, most centers have only limited capability, and some needed capabilities do not exist at all. Not only must the spectra be measured, but the conditions of a planetary environment, including temperature, pressure, and radiation, must often be reproduced.

Existing data sets for planetary objects and laboratory materials are scattered and not well documented. This is typical of most remote sensing research fields. The Planetary Data System project is being implemented in an attempt to overcome this problem. **The PDS should take into account the needs of the reflectance spectroscopy field by establishing at least one discipline node and several investigator nodes.**

New spectrum and image cube data handling and analysis software systems are particularly important to handle the expected very large data sets from the NIMS and VIMS spacecraft instruments and the similar ground-based telecope instruments about to become operational. Several image cube systems are under development (GARP, SPAM). GARP is almost entirely directed at mission support, and SPAM is largely an effort of the terrestrial remote sensing program. SPECPR is a one-dimensional spectrum processing system which is fairly mature. **At present, the capability to handle imaging spectrometer data sets of the volume expected does not exist.**

Future Applications and Requirements

The U.S. Solar System Exploration Program, as now planned , will place demands on the reflectance spectroscopy field far greater than in the past. Imaging spectroscopy techniques will increasingly dominate spectral reflectance studies. In addition to even more sophisticated and extensive telescopic studies of planetary reflection spectra, major spacecraft mission data sets with many orders of magnitude and more data volume for a variety of bodies will be available in the next decade. The Galileo and Mars Observer mission payloads contain reflectance spectrometers as do the strawman payloads for the CRAF, LGO, and Cassini missions. It appears that competing solar system exploration programs in other countries will also include these investigations.

It is recommended that efforts be accelerated in several critical areas. **Theoretical and laboratory studies aimed at interpreting planetary spectra from diverse surfaces are needed.** These should involve detailed measurements of well-characterized minerals and condensed volatiles (including environmentally controlled studies) appropriate for exploration of outer satellites, Mars, the Moon, comets and asteroids. Investigation of alteration and weathering processes and products (including the effects of irradiation) for these bodies is also needed. Development of accurate theoretical and analytical capabilities is required to extract the essential compositional information from complex spectra of the surfaces of these bodies. **Earth-based telescopic observations must be continued;** we must have information about the spectra and geochemical properties of solar system objects in order to properly plan and carry out spacecraft missions and to provide the realistic data sets necessary to develop and test analysis techniques. **Techniques for handling imaging spectroscopic data sets must be further developed** so that the rapid advances in instrumentation and spacecraft experiments yield comparable advances in the understanding of the geochemistry and geology of planetary surfaces. **Data sets should be cataloged and maintained in living data bases for better access by the scientific community.**

All this can and should be done while an emphasis on scientific issues and questions is maintained (see chapter 6).

Strategy and Implementation

Certain aspects of the reflectance spectroscopy program urgently require attention if the mission and science objectives discussed previously are to be met. These include critical research problems and other problems that are largely programmatic in nature. More detailed discussions of some of these problems and proposed solutions appear in chapter 7.

Mission Readiness

Spectra have been treated on an individual basis, and we have not had to be concerned with processing large quantities of data. Multispectral images have been similarly treated on an individual basis or for only a few bands. However, future missions (and telescopic investigations) will produce an unprecedented flood of spectroscopic data. A few tens of seconds of transmission from the Galileo NIMS or Mars Observer VIMS instruments can exceed the total of all existing telescopic spectra of the jovian system. An entirely new approach is necessary, and some are now being tested in a few laboratories. However, one of our key findings is that **there presently exists an appalling mismatch between the objectives of NASA (and foreign) planetary missions to conduct high data rate reflectance spectroscopy experiments and the present capabilities for data analysis and interpretation.**

We identify three critical research areas that require immediate attention in preparation for future planetary missions.

Large Data Sets and the Merging of Spectral and Image Analysis. Future missions will obtain spectroscopic data in the form of three-dimensional reflectance data arrays (image cube). As the spectral dimension is increased into the range of the 100 or more bandpasses necessary for spectroscopic interpretations, the problem of data management becomes acute. It is still common, however, for scientists and program managers to treat spectroscopy and image analysis separately. Although a few research groups are addressing these problems, the level of effort within the planetary reflectance spectroscopy program is low.

Enabling Instrumentation. Existing laboratory and telescope observing facilities must survive if the mission goals discussed above are to be achieved. Of the greatest urgency is the operation of existing spectrometers and other equipment. Funding for technical personnel is the greatest need in most laboratories, followed by support for maintenance and repair of facilities. A few new specialized facilities are needed.

Predictive Spectral Modeling. The goal of predictive spectral modeling is realistic in the view of some investigators familiar with recent developments in the field; however, the present level of effort in the program is modest, partly because technique development is not a high priority of science proposal review committees. Yet such an approach may be the only way to analyze efficiently the large quantities of data expected from new missions.

Vulnerability of a Leveraged Program

Attempts to maintain a balanced program with a broad scope in the face of mission delays and constraints on the research budget appear to have resulted in a progressive reduction of support for most individual investigators over the past 5 years, although new investigators were added and the proportion of the Planetary Geology Program funding for this field was apparently modestly increased. At the same time, the scientific and technical sophistication of the field has increased, thereby increasing the requirements for laboratory facilities, computational facilities, telescopic instrumentation, etc.

The reflectance spectroscopy effort is now highly leveraged, that is, high research output is possible only because other NASA programs, other government agencies, and universities are carrying many of the real costs of planetary reflectance spectroscopy research. In the short term, shifting costs to other programs or institutions appears to be desirable because it results in more research per dollar for the NASA planetary program. This leverage, however, works both ways: control of the program passes to others who do not necessarily share the objectives of the reflectance spectroscopy program. If the other programs default or change direction, the NASA planetary reflectance spectroscopy program is vulnerable.

Interface With Other Science and Program Areas

Because reflectance spectroscopy is a technique within the broader field of planetary science, **it is essential that there be strong cross-disciplinary ties among the investigators.** However, cross-disciplinary work does not always fit conveniently within NASA organizational and programmatic structures. The Planetary Astronomy Program handles much of the planetary data set acquisition and the related observational instrumentation support, but data analysis is the responsibility of the Geology and Geophysics Program or the Planetary Atmospheres Program. Geochemistry and extraterrestrial samples programs are also involved. Program management can promote efficient use of existing resources by **encouraging and funding consortia and cooperative research projects** among scientists within the reflectance spectroscopy program, and including outside investigators.

Today, NASA is involved in a very active terrestrial remote sensing program involving reflectance spectroscopy. The terrestrial program has in some ways exceeded the planetary program in capability and level of effort. There is now considerable competition between these programs for personnel and facilities. **We recommend that a specific effort be made to coordinate the reflectance spectroscopy efforts in technique development in the planetary program and in the terrestrial program.**

We recommend that immediate measures be taken to improve communications between the NASA reflectance spectroscopy program management and the mission-oriented activities in NASA, especially Galileo and Mars Observer. It is not clear that the mission planners or even the investigation team leaders are aware of the ongoing research requirements in reflectance spectroscopy, or that NASA management has been fully appraised of the mission reflectance spectroscopy drivers.

Education

University programs are a fundamental part of the NASA program, not only because of the science and technology produced, but also because new researchers, technical staff, and administrators are being trained. Yet the tendency in most government programs when funds are limited is to consolidate around government facilities. The NASA planetary program has resisted this tendency better than most agency programs. To train students, funding must be stable for a 3 to 5 year period, but this has not always been the case. **It is essential that student training continue and that new researchers continue to be brought into the field.**

Consequences of Funding Actions

For the past 5 years, although we have been told that the portion of the Planetary Geology Program funding for reflectance spectroscopy was modestly increased, the funding per investigator per year appears to have diminished. Furthermore, for the reflectance spectroscopy investigations planned for new missions (e.g., MOM/VIMS) measurement planning and data processing budgets are a factor of 3 to 5 too low to carry out the required work; this load is historically transferred to the basic research program, where it cannot be borne. **The highest priority must be given to stabilizing the program, preventing further deterioration of the funding base, and building that base to meet the mission requirements of the near future.**

We have identified possible scenarios for future management of the field:

Scenario 1. Continue the current downward trend in support per investigator and continue to apportion the budget cuts among investigators. It is the continuation of this trend that is of primary concern, for the broad science coverage and balance of the program are at stake. The demands of future missions cannot be met this way.

Scenario 2. A small increase in funding would stabilize the program, keep pace with inflation, and allow for a maintenance mode in which the program is intact but resources are not adequate to meet the critical mission challenges ahead.

Scenario 3. If a substantial increase in support were available, the program could be stabilized, and a new level of effort could begin on mission-related challenges. There would be a lag period of a few years for gathering personnel and equipment. Some investigators have taken on other research commitments as funding has diminished in the planetary reflectance spectroscopy effort, and these commitments will not be dropped immediately.

Scenario 4. A scenario unattractive to some investigators is the elimination of some investigators to maintain level or increased funding for others. This is the approach of consolidating around a few centers of excellence where facilities as well as investigators exist. In this case, it is difficult to maintain a balance, but it preserves a core capability which can be built on when (if) funding increases.

It is essential that the investigators in the reflectance spectroscopy program work closely with management to provide information and support. It is also important that investigators communicate effectively as a group. **An annual or biannual meeting of investigators and management to discuss research and programmatic problems, not to present research papers, would be useful.**

Chapter 2

Purpose and Scope of the Workshop

Purpose and Objective

The workshop was commissioned by the Planetary Geology and Geophysics Program of the NASA Office of Space Science and Applications, Division of Solar System Exploration. The purpose was to review the field of reflectance spectroscopy, particularly as it is relevant to the sponsoring Progam. The basis for the field, its contributions, present conditions, and future directions and needs were to be treated. The science and technique were to be considered, particularly in light of the need for future space mission support. The instructions were to hold a workshop and in other ways foster communication among members of the community, solicit opinions, and prepare a written report presenting a summary of the community conditions and impressions. The objective is to provide the Program with material based on which informed programmatic and budget decisions can be made.

Scope and Limitations

The scope of this report is limited to reflectance spectroscopy in the visible and near infrared regions and its application to remote sensing of planetary surfaces and atmospheres other than Earth. All aspects of the field are covered: spacecraft, telescope and laboratory measurement capability, previous science results, current and future problems, analysis and interpretation capabilities and techniques, and laboratory and theoretical studies of material properties.

Several other fields are closely related to remote sensing; they are discussed briefly below. It is important to realize that the relationships among all the remote sensing areas are symbiotic and complementary. No two techniques produce (to any great extent) the same information, but they do allow consistency checking.

Terrestrial remote sensing

The development of reflectance spectroscopy as a remote sensing tool occurred first in the solar system exploration program as applied to other solar system objects using ground-based telescopes. Application to air- and spacecraft-borne studies of Earth was recognized early, and development soon began, but in a way somewhat isolated from the planetary effort; the two programs were carried out in different parts of the organizational structure of NASA and with different philosophies. Today there is greater overlap in personnel, technologies, and philosophy, but the two programs are still administered separately.

The terrestrial program is now more advanced in flight measurement technology and available data sets. This trend probably will continue, because aircraft measurements can be made while NASA spaceprobe launch capabilities are being regenerated. Nevertheless, reflectance spectroscopy technique and science as related to the terrestrial remote sensing program are not treated in this study. The scientists and facilities of the two areas of application (planetary and terrestrial) should be more closely linked for the benefit of both areas. This will require coordination within the NASA organization.

Atmospheric studies

The application of reflectance spectroscopy to the study of the composition and physical properties of planetary atmospheres has been extensive and successful. Here we concentrate on scattering from solid surfaces, but aerosols or clouds contain solid or liquid particles and may show characteristic absorptions; the same physics and theory apply. We refer to this area occasionally, but it is not treated in depth, and there are serious omissions.

Emission spectroscopy

In the mid-infrared spectral region (about 5—50 μ) there are strong and complicated bands in the emission spectrum of many geologically important minerals. Absorption and emission features in this region of the spectrum arise primarily from molecular and lattice vibrations. This was realized before reflectance spectroscopy gained wide attention. However, problems in understanding and removing the effects of the physical properties of materials (e.g., particle size, packing) caused funding agencies to lose interest. Nevertheless emission spectroscopy as a remote sensing technique has strong potential for providing mineralogical information. In fact, such an investigation (TES) has been tentatively selected for the Mars Observer Mission. Emission spectroscopy could become a very effective complement to reflectance spectroscopy; reflectance and emission spectroscopy should probably be considered as tandem investigations, as has apparently worked out for the

Mars Observer Mission. However, emission spectroscopy is not so far developed as reflectance spectroscopy, and much more research is required to define its ultimate worth. It is not discussed further in this report.

Vacuum ultraviolet spectroscopy

Vacuum ultraviolet spectroscopy is concerned with wavelengths shorter than about 0.2 μ, where common atmospheric gases are strongly absorbing. For use in planetary science, this spectral region has had to await the development of observational facilities, such as the IUE (International Ultraviolet Explorer spacecraft) or Space Telescope, situated above the obscuring atmosphere. The interaction of high-energy photons with planetary materials primarily involves strongly allowed electronic transitions (charge transfer, exciton, and valence-conduction band excitations), resulting in very high optical densities. Most of the reflected flux is thus from first surface reflections, with very little transmitted component. For polished mineral surfaces in laboratory measurements, spectral reflectance is diagnostic. However, in particulate materials, spectral contrast is somewhat reduced, and the diagnostic features are somewhat degraded. The major difficulty with the technique in this spectral region is that the solar flux is very low. With our present instrumentation, only the close terrestrial planets can be observed with adequate signal-to-noise ratio.

Other remote sensing techniques

There are other remote sensing techniques funded under the Planetary Geology and Geophysics Program, including radar and radio thermal emission, that are not treated here. The field of monochromatic imaging is not treated here because it is directed at morphological studies and is more appropriately the topic of a separate report.

Chapter 3

The Field of Reflectance Spectroscopy

History

The reflectance spectroscopy technique has been used extensively only for the last 20 years because the radiation detector technology for measuring (with sufficient precision and spectral coverage) the reflectance spectrum of distant objects was not available previously. Even so, attempts have been made since the beginning of this century. When the ability to observe solar system objects effectively was developed, a wealth of observational data resulted; the theoretical and laboratory work to improve the technique followed quickly.

The excitement of initial and continuing discoveries using reflectance spectroscopy resulted in an increase in the number of scientists developing and applying the technique and in the funds supporting the work. The NASA Solar System Exploration Program was an early supporter and continues to support work in this field.

Reflectance spectroscopy is a very active and productive technique which is applied using ground-based telescopes as well as laboratory and theoretical investigations. Over 100 articles per year from about 25 active workers in the field appear in professional journals. Major discoveries have been made, and much of the early reconnaissance of several objects or object systems (e.g., asteriods) has been carried out (see chapter 3). The technique and instrument development have been driven by the telescopic observations. Essentially all existing reflectance spectra remote sensing data sets for solar system objects other than Earth were acquired using ground-based telescopes; a few sets have resulted from Earth-orbital telescopes.

With the success of the technique, nearly every advisory committee studying future planetary missions in the past 10 to 15 years has recommended that a reflectance spectrometer be included in almost every proposed mission payload. The technique is now considered so important for flight missions that NASA has declared it a facility experiment to be provided by the flight projects rather than by principal investigators, as is the spacecraft itself and as were the television imaging experiments.

But reflectance spectroscopy has not yet played a role in NASA solar system exploration program flight missions because of (1) the increasingly long lead time NASA requires for development and flight of spacecraft instruments, (2) the lack of initiative for new experiments caused by the great success of the imaging systems of the early lunar and planetary missions, and (3) the hiatus in planetary missions resulting from budget cuts and NASA priorities over the past 10 years. Nevertheless, a reflectance spectrometer was chosen for the (later canceled) Lunar Polar Orbiter mission in 1975. It apparently was to be an instrument on the Comet Halley flyby-Temple 2 Rendezvous mission, for which instruments were never formally selected after an announcement of opportunity was circulated in 1976. In 1976, the Near Infrared Mapping Spectrometer (NIMS) experiment was chosen for the Galileo Project; the instrument has been built and is awaiting the eventual launch of the spacecraft (scheduled for 1989 or 1991). The Mars Observer Mission (MOM) also has a reflectance spectrometer (VIMS), selected in April 1986. The Comet Rendezvous Asteriod Flyby mission (CRAF) announcement of opportunity described a facility reflectance spectroscopy instrument as a prime candidate for the payload, and Lunar Geoscience Orbiter and Cassini mission science working groups have seriously recommended this investigation. Because of the impending mission involvement, the field of reflectance spectroscopy has recently evolved as a subdivision of the planetary exploration program, and the specific activities of the field have been tailored to accommodate specific mission capabilities.

Reflectance spectroscopy has become increasingly important in the area of terrestrial remote sensing. However, the focus of this report is the use of reflectance spectroscopy in planetary studies.

A related area of remote sensing that was active 20 years ago and has again become active is emittance spectroscopy. This field takes the general approach used in reflectance spectroscopy farther into the infrared spectal region, where thermal emission is the dominant source of radiation from planetary surfaces and atmospheres. Much of the reflectance spectroscopy measurement and analysis approach still applies, and the physics of the emission process is almost totally controlled by molecular processes. This area is not treated here.

Science Focus

The primary purpose of planetary geosciences (e.g., geology, geophysics, and geochemistry) and atmospheric sciences is to determine the nature, origins, and histories of the solid bodies and atmospheres of solar system objects. The majority of terrestrial geoscience investigations rely on mineralogy as a critical information source, and mineralogical information is equally critical to solar sytem object investigations. Specific mineralogy is not only a measure of the initial elemental composition of an object but also a direct indicator of the thermodyamic conditions experienced by at least parts of the object throughout its history. The molecular and particulate constituents in the atmosphere and exchanged with the surface are equally important to the study of these objects.

Reflectance spectroscopy provides information on the type and phase abundance of surface mineral assemblages and atmospheric constituents, and hence insight into the history and processes operative for each object. Reflectance spectrophotometry also provides information on the physical characteristics of these materials. In combination with other data sets, such as elemental compositions from gamma- and x-ray spectroscopy (which give elemental abundances), the mineral properties derived from reflectance spectra provide a powerful means of investigating planetary objects. Reflectance spectroscopy constitutes one of the very few and sometimes the only remote sensing technique available for determining mineralogy of most solar system objects for the foreseeable future.

By characterizing an important subset of the surface and atmospheric constituents (mineral or cloud species, composition and abundance, gaseous species) of planetary bodies, reflectance spectroscopy provides a basis for extension of data derived from spacecraft landing sites and from returned samples and meteorites.

The field consists of both science and technique, as is true of most experimental and measurement-oriented research. The science is a mixture of (at least) geology, geophysics and geochemistry, physics, and chemistry and is centered on determining the mineralogy and composition of solid objects and their atmospheres and working out the physical and chemical processes operating to create and alter them. This basic information is used by a wide variety of scientific disciplines. A good understanding of the technique is required for the science to be properly done, and the technique itself is still subject to major improvements and new measurement discoveries. Thus, students and professionals must be qualified in the use of the technique in order to contribute to the first-order development of the field. The long-term goal is to make the technique a straightforward analysis method easily understood by nonspecialists. As long as the technique is effective and the information it provides is useful, there will be a need for scientists with a wide range of orientations, from nearly pure technique development to nearly pure science application.

The evolution of this field has reached the point at which the name *reflectance spectroscopy* may no longer be appropriate. The term *reflectance spectrophotometry* may prove to be more desirable in recognition of the fact that future planetary exploration missions will return both spectral and photometric information of high spatial as well as spectral resolution. Future spectral analysis activities will expand beyond identification of new mineral species and will include determination of absolute abundances of particular species and phases within a given spatial unit. For this more difficult goal, precise measurements of intensity are required.

Areas of Effort

The primary planetary reflectance spectroscopy data set results from the measurement of reflected sunlight from a planetary object and the calibration of the measurement instrument and the conditions so that the ratio of reflected to incident sunlight as a function of wavelength (spectral reflectance) can be calculated. The spectral reflectance of a particulate surface depends on many factors; mineral type, chemical composition, abundance, and grain size are the most important. Most minerals show diagnostic absorptions due to molecular vibrations, electron charge transfer, conduction bands, and electronic transitions. Second-order effects on absorption band presence and wavelength position include viewing geometry, particle packing, and temperature. Other effects such as weathering (which produces other minerals) and sputtering can be major or very minor. The magnitude of these effects depends on the exposure time, intensity, and the exact nature (i.e., mechanism) of the weathering and sputtering processes.

The technique of reflectance spectroscopy involves the interpretation of the planetary reflectance spectra to detect these absorptions, to identify the mineral phases present, and, through available models (theoretical and empirical) to determine abundances and physical states. It can often work in the opposite sense, that is, determining what is not present on the surface of a body—a result of great significance in refining existing models and developing new models of surface properties.

The theoretical models and laboratory measurements of candidate materials from which the interpretation of the planetary data set can be derived are of primary importance. The fundamental data set used for interpreting the planetary spectra and determining the composition of planetary surfaces is the laboratory reflectance spectra of minerals, rocks, gases, and ices (which themselves are minerals) under simulated planetary conditions. The spectra of many hundreds of (planetary surface analog) materials have been measured, allowing many of the discoveries cited in chapter 3. Theoretical models to calculate reflectance spectra from basic material optical properties and the use of examples from laboratory measurements are critical for efficient interpretation of the coming wave of new data; laboratory measurement of all materials under all relevant conditions are time consuming, expensive, and virtually impossible.

The successful application of reflectance spectroscopy requires contributions from four distinct and equally important areas:

Development, operation, and maintenance of laboratory, telescopic, and flight instrumentation and related personnel and facilities

Measurement and archiving of spectra and supporting parameter data bases for solar system objects and candidate materials in the laboratory, using telescopes, spacecraft, and laboratory systems, to address well-formulated and significant scientific questions or technique development needs

Development of reflectance spectroscopy theory, rigorously based on radiative transfer theory, along with interpretive calibrations and procedures from which procedures can be developed for deriving chemically, mineralogically, and geologically significant properties from spectral data sets

Interpretation of the observational data set to determine the planetary surface and atmospheric properties and integration of those properties with other available information into an appropriate model that addresses the specific scientific issue raised in the original statement of the problem that motivated the measurement

Instrumentation, interpretive calibrations, laboratory data sets, and theoretical modeling are enabling technologies. They permit acquisition of spectral data for solar system objects and interpretation of those data sets to derive surface mineralogic and physical parameters and certain atmospheric properties. Proper data base management procedures must be followed to ensure that the data sets are and will continue to be useful to the community at large. All these activities are essential to the successful application of reflectance spectroscopy to planetary science problems, and most must be carried out as integrated activities with participating scientists working in and familiar with several areas.

Measurement Considerations

The fundamental measurement of reflectance spectroscopy is the ratio of reflected sunlight to incident sunlight on an area of a solar system object. This measurement is made using detectors and wavelength discriminating devices that (ideally) yield a spectrum of light intensities as a function of wavelength, polarization state, location on the surface of the object, and the relative angular relation between Sun, object, and observer at the time of measurement.

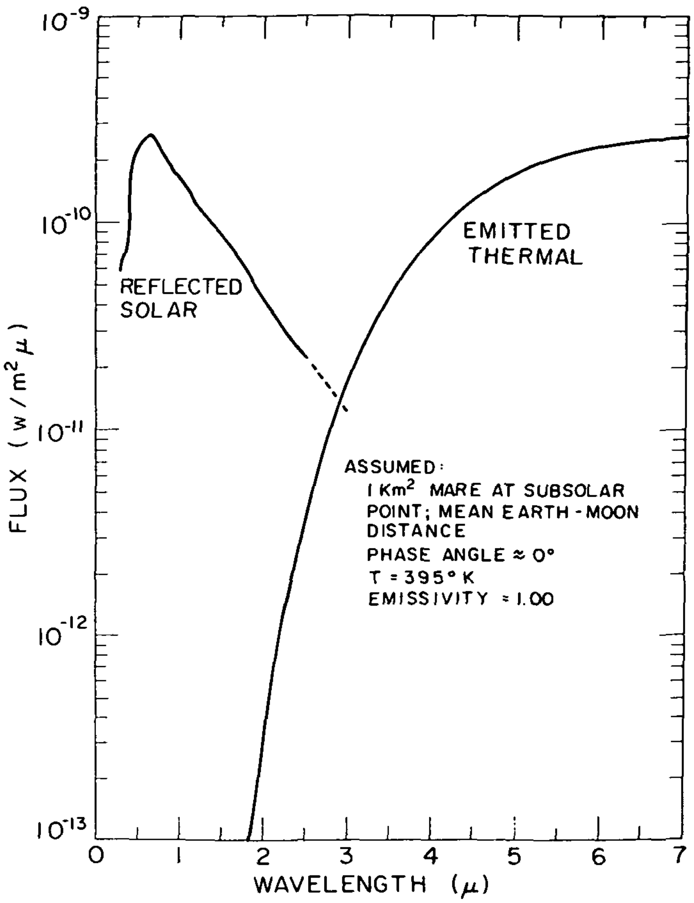
Reflectance spectroscopy depends on an illuminating source of light, which in planetary studies is the Sun. As a quasi-blackbody radiator at 6000 K, the Sun is an efficient radiator of energy in the near ultraviolet, visible, and near infrared spectral regions. However, somewhere in the spectral region between about 1.6 and 5.0 μ for the terrestrial planets (depending on the distance of an object from the Sun), the planetary body itself becomes a radiator and emits as much or more thermal energy from its surface as the energy of sunlight that it scatters back to space (see the figure). When the emitted energy becomes the major fraction of the reflected energy at a given wavelength, interpretation of the measured spectrum becomes difficult to impossible. At ultraviolet wavelengths shorter than about 0.4 μ the solar flux decreases rapidly. Therefore, the region of most interest covers the wavelength interval from about 0.3 μ through about 5.0 μ, where reflected incident solar light is usually the primary source flux from surfaces and atmospheres of sufficient strength to be measured accurately.

Physical Basis

There is a direct link between the phenomenological aspects producing reflectance (or absorption) spectra and the regions of the electromagnetic spectrum where features are observed. In the wavelength range 0.2—5.0 μ, spectral features have origins involving electronic, vibrational, and rotational energy levels. These transitions are further subdivided into anion$\rightarrow$cation electron transfer (e.g., $O^{2-} \rightarrow Fe^{2+}$) in the near ultraviolet region, metal$\rightarrow$metal intervalence electron transitions (e.g., $Fe^{2+} \rightarrow Fe^{3+}$ or $Ti^{3+} \rightarrow Ti^{4+}$ in pyroxenes) in the visible region, intraelectronic or crystal field transitions (e.g., t2g$\rightarrow$eg energy levels of 3d orbitals of Fe^{2+} in olivines) in the visible near infrared region, and vibrational and rotational transitions of specific functional groups of molecules or anions that are observed in the near infrared region as combination and overtone bands (e.g., H-O-H or CO_2) or anions (e.g., $O\text{-}H^-$ or CO_3^{2-}) in, for example, clay silicates and carbonates.

In general, wavelengths (energies) of these transitions are diagnostic of cations and their crystalline environments, or of functional molecular or anionic groups, in minerals. However, additional theoretical analyses of spectra and energy levels, utilizing crystal chemistry, bonding models, quantum theory, and selection rules, are often required to aid the assignment of features in reflectance spectra. On the other hand, laboratory spectral measurements of correlative mineral assemblages or rock types believed to be models of surfaces of planets have had to be made under physical conditions simulating their regoliths. An ongoing research area is the measurement of spectra at different temperatures, confining (atmospheric) pressures, particle sizes, grain size packings, and modal mineral proportions. Thus, laboratory and theoretical calibration studies are a prerequisite for detailed interpretations of remote-sensed reflectance spectra.

The light scattered by a surface or atmosphere can be the result of a very complex interaction. **First surface reflections and diffuse scattering from several materials of several grain sizes can be mixed in a single measurement for one resolution element.** *For many solar system materials, reflectance spectra can be considered as* **primarily a function of the mineral or molecular species and their abundance and composition. For solid surfaces, the measurement usually involves only the upper few millimeters of the surface material.** *These materials at ultraviolet, visible, and* **near infrared wavelengths exhibit absorption features due to molecular vibrations and to electronic energy transitions of several types. This first-order effect is modified by a number of second-order effects, such as geometry and particle size, which usually alter the spectral properties only in a way slowly varying with wavelength. There are materials which are important exceptions, such as various ices and oxide minerals, where particle sizes have a major first-order effect on the absorption band properties in the spectrum. Thus the problems of complex scattering and mixtures below the spatial resolution element are very important, sometimes making it impossible to separate atmospheric and surface effects.**



RADIATION FROM MOON [1km² of mare] AT EARTH

Chapter 4

Contributions

Surface composition and mineralogy of a solar system object are fundamental properties that must be determined in order to understand the history and origin of the body. Reflectance spectroscopy has proven to be the most powerful available technique for determining thick atmospheric and surface lithologic composition by remote sensing. Planetary scientists using Earth-based telescopes and spectrometers have used this technique to determine the primary surface and atmospheric constituents of all the major bodies in the solar system, from the nearby Moon to distant Pluto. Essentially everything we know about surface mineralogy, except for Earth and the Moon, for which we have documented samples, has resulted from reflectance spectroscopy used as a remote sensing tool and with ground-based telescopes.

The basis for the credibility of the technique lies in both past discoveries of planetary surface and atmospheric properties and confirmation of predictions by groundtruth. These are discussed below.

Discoveries

The major scientific contributions made to planetary science through the use of reflectance spectroscopy and related techniques, such as multicolor photometry and polarimetry, are many and varied. Perhaps the most effective way of communicating the extent and nature of these contributions here is to simply list examples.

Mercury

Lunar-like surface regolith (1960)
Low ferrous-iron crust (1975)
Spectrally distinct surface units (1975)
Sodium emission (1985)

Venus

Carbon dioxide atmosphere (1932)
Isotopic forms of CO_2 (1962)
CO, HCl, HF in atmosphere (1967)
Sulfuric acid in clouds (1973)
Sulfur in clouds (1975)
Sulfur dioxide in atmosphere (1979)
Highly oxidized surface materials (1986)

Moon

No atmosphere (1859) [using polarization data]
Surface rough and loose (1865)
Basaltic surface (1908) [confirmed in 1963 and 1968]
Spectrally distinct surface units (1918)
Surface very porous (1918) and fragmental (1945)
Surface is impact debris, glassy, some iron (1953)
Surface darkens with age (1955)
Surface particle sizes to 0.3 μ (1960) [polarization data]
Solar wind darkening (1962)
Large amount of opaque phases (1963)
Dominant particle sizes about 10 μ (1963)
Olivine or clinopyroxene present (1968)
Vitrification darkening by impacts (1970)
Major highland rock units defined (1972)
Existence of many units unsampled by Apollo (1978)
Olivine-rich material in some central peaks (1982)
Existence of ancient, pre-basin basalts (1983)
Anorthosite deposits in Orientale and Nectaris basin rings (1984)
Near-side crust is laterally and vertically inhomogeneous (1986)

Mars

Surface of Fe-oxide and silicates (1961)
Carbon dioxide in atmosphere (1966)
Hydrate and water-ice on surface (1969)
Clay minerals in atmospheric dust (1971)
Mafic silicates on surface (1972)
Carbon dioxide ice at south pole (1976)
Water ice at north pole (1979)
Mg-OH and clays on surface (1981)

Asteroids

Particulate surfaces (1964)
Vesta is a differentiated body with basaltic surface (1970)
Many distinct compositional classes (1971)
Some composed of meteorite-like mineral assemblages (1975)
Some dynamic families have common parent bodies (1977)
Radial distribution of classes in belt (1982)
Some asteroids are olivine rich (1983)
Some have mineralogically distinct surface units (1983)

Near-Earth asteroids a different population
Organic-rich composition of some asteroids (1984)
Metamorphic heating declines rapidly with solar distance (1985)
FeO content increases rapidly with solar distance (1986)

Giant Planets
Methane and ammonia in atmospheres (1930s)
Hydrogen atmosphere (1960)
Vertical cloud structure and particulate properties (1960?)
Stratospheric hydrocarbons (late 1960s)
D/H ratios in Jupiter (1972)
CO in stratosphere of Jupiter (1975)

Satellites of Jupiter (Galilean)
All have leading/trailing spectral asymmetry (1927)
Io
  No water ice (1972)
  Sulfur rich (1973)
  Sodium cloud (1973)
  Sulfur dioxide gas and ice (1979)
  Longitudinal distribution of SO_2 (1980)
  Albedo-temperature relationship for hotspots (1985)
Europa
  Water ice (1972)
  SO_2 on trailing side (1981)
  Sulfur on trailing side, magnetospere modification (1985)
  Ganymede - water ice (1972)
  Callisto - water ice (1972)
  Hemispheric dichotomy in surface (1975)
  Magnetospheric effects on trailing hemispheres (1981)

Satellites of Saturn
Methane on Titan (1948)
Complete cloud cover on Titan (1972)
Water ice surfaces (1975)
Bright hemisphere of lapetus is water ice (1976)
Dark hemisphere of lapetus "carbonaceous rich" (1983)

Satellites of Uranus and Neptune
Surface water ice (1980)
Dark carbonaceous-like component (1983)
Methane ice, solid or liquid nitrogen on Triton (1984)

Rings of Saturn
Water ice (1970)
Dark non-icy component (1973)
Dark component may be carbonaceous (1980)

Rings of Uranus
Very low albedo, non-icy (1977)

Rings of Jupiter
Low albedo, non-icy (1980)

Comets
Emission lines from CN, C_2, C_3, (1882)
Emission from OH (1943)
Emission from ionized water (1974)
Neutral water (1985)
Organic compounds (1986)

Pluto
Methane ice (1976)
Methane gas (1980)

Groundtruth

Groundtruth is important to the effectiveness of remote sensing techniques both for confirming and refining the techniques and for allowing the extension of more sophisticated interpretations of unsampled locations. Except for Earth (which we exclude from this discussion), we have documented surface material samples only for the Moon. Although reflectance spectroscopy was not sophisticated when the Apollo program began producing samples, it was possible to make predictions about the mineralogy of landing sites before samples were returned. In particular, the prediction of the titanium content (in ilmenite) of the Apollo 17 site was successful and helped confirm the technique. Well before the Apollo program, predictions from lunar colors and early spectra called for a basaltic surface material. In 1967, the importance in the lunar mare soil of pyroxene with a Hedenbergite composition was predicted from spectra.

Meteorites are now accepted as samples of asteroids (with a few exceptions), with the clearest associations being in the cases of basalt meteorites (Vesta) and dunite meteorites (class A asteroids). In general, it appears that large biases exist in delivery of meteorites to Earth, so that some important classes of asteroids have not been included in sample studies.

Experiences from both the Viking mission to Mars and the Voyager mission to the Galilean and outer solar system satellites in general show that reflectance spectroscopy measurements and most of the interpretations are at least reasonable. In a sense, these missions provided a measure of groundtruth by at least relatively closeup observations at higher spatial resolution (but lower spectral resolution and reduced spectral range) that confirmed earlier Earth-based observations. In fact, some "discoveries" commonly attributed to these missions were actually made years before by spectroscopy from Earth. However, the lack of any direct surface mineralogy investigation on these missions makes comparisons difficult.

Summary

Laboratory spectroscopy of terrestrial minerals and rocks, various gases, frosts, ices, and synthetic compounds, and extraterrestrial materials such as meteorite and lunar samples have shown that there are diagnostic features that allow discrimination of the mineral assemblages on planetary surfaces and hence provide insight into the composition of these objects. Most meteorite mineral assemblages have been found on asteroids, and our knowledge of meteorite materials has been extended to specific places in the solor system. The bulk of lunar sample spectra are for Apollo landing site soils and provide good background for understanding the alteration and agglutinate formation process of the lunar environment. Minerals that have been identified spectroscopically in lunar soils include low-Ca pyroxene, high-Ca pyroxene, plagioclase, olivine, Fe-bearing glass, and Fe- and Ti-oxides (opaques). This information provides a basis for mapping widespread areal units on the Moon using telescopic surveys, information otherwise presently inaccessible. This is just one example of how reflectance spectroscopy should be intensely applied to all bodies in the solar system. With most of the solar system unexplored, the vast bulk of the work in the new field of planetary spectral reflectance remains to be done. In future decades more discoveries will occur, and fundamental spectral information needed to understand the origin and evolution of the solar system will develop.

Chapter 5

Current Capabilities and Resources

This chapter presents a list and short description of the existing capabilities and facilities of research centers which are utilized for planetary studies using reflectance spectroscopy. These are given in terms of (1) the ability to derive information from measurements and (2) the facilities and personnel to make the measurements and to interpret them. The interpretive capabilities are presented according to the goals and objectives of the field and the degree to which they have been achieved. The facilities and personnel are discussed by identifying the principal research centers and outlining the research topics treated at each, as well as by listing the facilities available for reflectance spectroscopy at each research center. Much of the information is presented in table or matrix form to make it easier to comprehend.

This report should be used to evaluate the scope and direction of the community as a whole and not to review individual research centers. Individual investigators are not identified. Full evaluation of the field is beyond the scope of this study. These summaries and outlines are reasonably comprehensive, but because the material has not been fully reviewed, there are probably some errors and omissions.

It must be noted again that there were severe limitations on the scope of this study, and areas such as terrestrial remote sensing are not considered here.

Objectives and Status

The goals and objectives of reflectance spectroscopy are discussed in chapter 3. An attempt is made here to review the current capabilities for deriving scientifically useful information for solar system studies using the reflectance spectroscopy technique by describing the degree to which these goals and objectives have been met. The objectives are listed in order of increasing difficulty:

Identify the *presence* of specific materials and map their distribution.

Determine the *abundance* of materials present.

Estimate the *composition* of materials.

The current status of the accomplishment of these objectives and the goals to be pursued in the future are outlined by objective in, respectively, tables 1, 2, and 3. It can be seen from these three summary tables that the current and anticipated capabilities address fundamental questions about the nature of the solar system.

Facilities and Personnel

To achieve the goals and objectives described in chapter 3 and above requires three closely interrelated data acquisition and analysis activities:

Obtain reflectance data for planetary surfaces through a well-planned *data acquisition program* (ground-based and Earth-orbital telescopes and deep space probes).

Establish a solid foundation of *laboratory reflectance spectroscopy measurements* for materials and conditions appropriate for the surfaces studied.

Develop accurate *theoretical and applied analysis capabilities* to interpret the data and extract the desired information.

Each of these activities must be motivated by basic scientific questions about the solar system. This is an experimental science, and it is measurement oriented. Measurement, however, should never be an end in itself but rather a means to answer a scientific question.

These activities require the development, maintenance, and operation of adequate facilities (telescopic, laboratory, computer, technical personnel, etc.) to carry out the data acquisition and analysis objectives. A deficiency exists. There is no separate funding or program base to cover facility support. Budget line items covering this need which are included in research proposals are routinely cut by review committees. A formal program is needed to provide long-term (3 to 5 years) stable support for basic facilities at designated centers of excellence.

Many research centers have research goals and facilities that are involved with and funded by other (nonplanetary or even non-NASA) programs. The planetary research pursued by these groups is often heavily or totally subsidized by other programs and agencies. Therefore, it should not be assumed that all or even most activities, facilities, and personnel mentioned in the following sections are funded directly by the Planetary Geology and Geophysics Program. The community is in fact highly leveraged in that a little support from the Program is buying much capability. Slight decreases in support by the Program could result in major losses in capability, as researchers can no longer extend their support under other programs without jeopardizing those programs.

Participating Organizations and Principal Programs

There are at least 18 university, NASA center, and U.S. Geological Survey locations at which at least one investigator is active in reflectance spectroscopy research as applied to planetary studies. These research programs vary greatly in size and breadth. About half of the programs have only one investigator. The total number of investigators is about 30, and many of these do not devote full time to this area.

Table 4 summarizes these organizations and the principal research topics. None of the programs encompasses all the areas required in the field, nor should they. There is considerable interaction among individuals and research centers concerning research topics and programs.

Because the field is young, many investigators continue to communicate with their home center after leaving. The small size of the community and the restriction in funds, especially recently, has resulted in very little overlap in facilities and research programs among groups.

Planetary Spectrum Measurement Facilities

The acquisition of reflectance spectroscopy data depends on the capabilities of instruments on Earth-based or Earth-orbiting telescopes and on future instruments carried on planetary spacecraft. These facilities produce the primary data required to investigate the nature and composition of planetary surfaces. The information about solar system materials derived from the correct interpretation of these data is the reason for the existence of this field of planetary science. The capability of these facilities and the quality of the data they produce thus control developments in the rest of the field. The measurements made using these facilities are guided by scientific questions and by the technology that can be incorporated into the facilities.

Essentially all the reflectance spectra for planetary objects have been obtained using ground-based telescopes. No U.S. spacecraft has carried a reflectance spectrometer to a planetary object. The only U.S. spacecraft that has made planetary spectral reflectance measurements is the IUE. Thus, it can be argued that the ground-based telescope facilities are the most important to the field at this time and for the next several years, until the Space Telescope and the Mars Observer begin returning data. In fact, the Space Telescope does not have an instrument in its first payload to measure reflectance spectra other than in the ultraviolet and blue spectral regions.

There are only two centers at which major ground-based telescope facilities are actively used for reflectance spectroscopic studies of solid surfaces (University of Arizona and University of Hawaii). The Jet Propulsion Laboratory has significant facilities but most of their observations in the recent past have been made with the Hawaiian facilities. Current planetary data acquisition facilities are summarized in table 5.

Laboratory Spectrum Measurement Facilities

The measurement of the optical properties of candidate and sample materials for solar system objects is critical for interpreting the planetary data set. It provides comparison spectra of known materials for direct interpretation of spectra for unexplored planetary surfaces. It provides fundamental data on physical and optical parameters required for use in theoretical models for calculation of reflectance spectra. It also can be used to create model data sets, which are necessary for developing and testing the computer and automated data processing and analysis systems required by the next generation of primary planetary data, from imaging spectrometers.

This laboratory measurement capability has grown the most of the various facilities for reflectance spectroscopy research in the recent past. This is because there is so much to be done. There are so many categories of materials to be studied: ices, frosts, hydrates, organics, salts, silicates, oxides, metals, etc. There is such variety in the conditions under which they must be studied to be relevant: cold temperatures of outer solar system objects, high temperatures of the surface of Venus, atmospheric conditions on Mars, radiation conditions of the Galilean satellites, volatile environment of the subsurface of Mars, conditions of cometary nucleus surfaces, etc. This requires a wide variety of laboratory facilities: environment chambers of many sorts in which conditions can be controlled while measurements are made, irradiation systems, spectral coverage over a wide spectral range requiring several different detector and dispersion technologies, goniometers, microsample systems, etc. These are probably too complex for any one institution. Capabilities are needed for detailed studies of the spectral reflectance properties of materials (under both diffuse and bidirectional geometry) as well as for studies of the general photometric properties of surfaces. In addition, these facilities must have data processing capabilities to reduce and analyze the measurements.

The capabilities of existing research facilities available to planetary scientists are summarized in table 6. There are at least 13 research centers with laboratory reflectance spectroscopic measurement capability, and at least 9 of these have only one investigator active in reflectance spectroscopy. At least 5 research centers report no capability. The facilities in table 6 overlap very little in application focus; these facilities are heavily used.

Planetary Spectrum Data Sets

Currently available spectral reflectance data for planetary surfaces have been obtained almost completely through the use of Earth-based telescopes. This will continue to be the case until the Mars Observer returns data in 1991, followed by Galileo, CRAF, and the Observer series LGO, NEARS, etc. The existing and expected new telescopic data sets are critical to planning the new mission investigations as well as preparing the data handling systems and the interpretive techniques for the deluge of data expected.

In addition to the telescopic spectra, there are a few Mars reflectance spectra in the infrared for wavelengths longward of about 2.5 μ from the Infrared Spectrometer (IRS) investigation on Mariner Mars 6 and 7. Also, the International Ultraviolet Explorer (IUE) Earth-orbital spacecraft has produced a large number of ultraviolet reflectance spectra of the Galilean satellites and comets.

There has been no formal (Program) organization of the available reflectance data of planetary surfaces; however, individual investigators have imposed an informal structure. Many data sets are now being restored, mainly at the University of Hawaii, where most of them were acquired, as part of the Planetary Data System program. There are significant spectroscopy data sets for almost all planetary objects; the largest are for the Moon, Mars, and asteroids. The principal planetary spectroscopy data sets are maintained at the University of Hawaii, the University of Arizona, the Jet Propulsion Laboratory, and Brown University.

Laboratory Spectrum Data Sets

Preliminary surveys of the spectral properties of solar system materials exist for terrestrial, lunar, and meteoritic samples and for rocks and minerals, condensed volatiles, and frosts. These data provide a foundation for interpretation of planetary data. However, a measure of the wide range of conditions of these data sets is the fact that no meaningful summary of the existing data sets could be prepared for this report.

Many data sets do not contain sufficient characterization of the materials and are thus inadequate for the requirements of applied reflectance spectroscopy over the next decade. Laboratory measurements were often made for specific applications and not to support a database. Only certain spectral ranges were covered, and information on sample and measurement conditions was not recorded. More attention should be paid to properly characterizing samples and measurement conditions and to placing the data in a standard format. This library task is just one of many that have been uncovered by the Planetary Data System effort. A committee composed of members of the spectroscopy community should be formed to promote better archiving and retrieval of laboratory reflectance spectral data sets.

New laboratory measurements of materials will be required for future investigations. These should be made at several laboratories and should focus on the needs of specific research programs. Theoretical models should be used to extend laboratory measurements and to help avoid massive and detailed measurement programs. The measurements should be archived for general use.

Spectrum Analysis Capability

There are several types of spectrum analysis capabilities: computer hardware and operating systems, data processing and analysis software systems, and interpretive techniques and algorithms. All research centers involved in reflectance spectroscopy research must have spectrum data set handling capabilities.

The computer facilities being used for theoretical and applied analysis projects using reflectance spectroscopy are summarized in table 7.

The software data handling system is especially important, particularly for the large imaging spectrometer data sets expected from ground-based telescopes and spacecraft instruments and for the associated laboratory data libraries. Several integrated systems have been developed specifically for reflectance spectrum handling. SPECPR, which deals with single spectra, was developed to handle one-dimensional data sets. It is maintained at several centers, and exchange of developments is fairly widespread. Image cube data processing systems (GARP and SPAM) have also been developed. These systems handle the data sets produced by imaging spectrometers and deal with image cubes as well as with image planes and individual spectra. GARP and SPAM have been exchanged between the development centers and are running in a preliminary fashion at one or two other centers. There is a need for innovative analysis of data sets using "artificial intelligence" techniques.

The current status of interpretive capability is more difficult to summarize, since reflectance spectroscopy is not a "black box" science, for which every input has a uniquely interpretable output. Although analysis has certainly progressed well beyond simply "matching" spectral curves, a number of areas need considerable effort and testing, especially to obtain the second and third objectives of reflectance spectroscopy (tables 2 and 3) which provide the type of quantitative information necessary to address many geochemical problems.

Investigators

The individuals participating in spectral reflectance research applications are the most important assets of the field. The number of scientists and students actively working on spectral reflectance applications in planetary science are summarized in table 7. Approximately 30 investigators are currently using reflectance spectroscopy for planetary studies. Only two research centers have three or more investigators. This indicates a rather thin spread of personnel, with the associated risk of too little communication, especially since many of the investigators have unique areas of specialization.

About seven of the research centers currently train students for work in the field. The average number of new Ph.D. researchers from all education programs is estimated to be one to three per year. Not all or even most of these students enter the NASA Planetary Program.

Very few investigators receive all their funds from planetary investigation programs; some are unfunded. A large percentage of participants contribute their efforts to the Planetary Program at a level much higher than that of their funding by the Planetary Program. This highly leveraged involvement carries with it an inherent lack of stability for the planetary reflectance spectroscopy community and the planetary program as a whole.

Table 1. Detection and Identification of Specific Materials

Planetary Body	Status	Goals
Mercury	Surface properties appear to be similar to Moon; no specific minerals identified yet Na in atmosphere, presumably sputtered from Na-bearing minerals in the regolith	Identify the minerals and any alteration products of the surface
Moon[a]	Pyroxene, olivine, Fe-Ti-bearing glass detected Plagioclase detected in basaltic mare Shocked and unshocked plagioclase (anorthosites) identified in highlands Agglutinates detected	Resolve superimposed features of low- and high-Ca pyroxene, olivine, and plagioclase Detect Fe-bearing glass (low-Ti) Confirm detection of plagioclase Detect ilmenite Detect Ti^{3+}-bearing pyroxenes and glasses in mare basalt regions
Mars	Fe^{3+}-bearing phases and amorphous ferric oxides detected Pyroxenes detected locally Olivine suspected Clay minerals detected Crystalline ferric oxides can be detected (if present) H_2O frost detected Dust characterized	Resolve superimposed features of pyroxene, olivine, and atmospheric bands Determine characteristic properties of plagioclase and opaques for Mars material Identify mineral compositions and structures of clay minerals Distinguish overlapping features of H_2O (ice and adsorbed) and atmospheric CO_2 Search for minerals hosting SO_4^{2-} and CO_3^{2-} anions Determine nature of oxide and oxyhydroxide phases, especially <100 nm
Asteroids	Pyroxene, olivine, plagioclase detected Organic polymers suspected Opaques detected qualitatively OH detected Metal suspected	Distinguish differentiated metal from chondritic metal Understand physical state of metal in regoliths Resolve superimposed features of low- and high-Ca pyroxene, olivine, and plagioclase Determine relative abundance and composition of silicates and organics and the presence and amount of hydrates and water
Outer Satellites	SO_2 detected on Io Sulfur component detected on Europa, suspected on Io H_2O frost detected (± unknown contaminants) on Europa, Ganymede, Callisto, Tethys, Dione, Iapetus, Rhea, Enceladus, Hyperion, Miranda, Ariel, Umbrial, Titania, Oberon CH_4 detected on Pluto, probably on Triton N_2 (solid or liquid) probably detected on Triton	Identify silicate, carbonaceous, and other components Identify other volatiles and frosts, e.g., presence of mixtures such as NH_3+H_2O, form of sulfur and sodium on Io, irradiation products

[a]By remote sensing for unsampled localities, not from returned samples.

Table 2. Determination of Abundance of Materials

Planetary Body	Status	Goals
Mercury	Low ferrous iron content of surface	Quantify amount and type of silicates Determine mineralogy of regolith Identify source mineral of Na
Moon	Relative abundances of olivine measured Relative abundance of pyroxene measured Upper limit of pyroxene determined for highland fresh surfaces Relative maturity described locally (agglutinate content)	Determine modal abundances for unsampled areas with the following precision: pyroxene ±5% olivine ±10% plagioclase: anorthosites identified and mapped other rock types ±10% glass (Fe bearing) ±10% glass (Ti^{3+} bearing) ±10% opaques ±2% *alteration products* (agglutinates) ±10% Map local and global surface composition
Mars	Fe_2O_3 estimated Lower detection limits set for some minerals: clay silicate minerals <±5% crystalline and magnetic ferric oxides <1%	Determine modal abundances with the following precision: pyroxene ±5% olivine ±10% plagioclase ±10% clay silicates ±5% carbonates, sulfates, nitrates ±5% opaques ±5% sulfur compounds, specifically sulfate minerals ? H_2O frosts ±5% alteration products ±10% Clarify hydroxylated minerals (clay silicates, iron oxyhydroxides, basic ferric sulfates) Map local and global surface composition
Asteroids	Relative abundance of orthopyroxene and olivine estimated to ±5%	Determine amount of water Determine silicate/metal ratio Identify specific carbonaceous chondrite classes Determine FeO/(MgO + FeO)
Outer Satellites	Quantitative mapping of SO_2, sulfur, sodium on Io Water abundance estimated to ±10% on icy bodies	Determine silicate/frost ratio Determine relative proportions of different types of silicates Determine relative proportions of different types of frosts

Table 3. Composition of Materials and Nature of Alteration Products

Material	Status	Goals
Pyroxene	General systematics identified in early 1970s: Ca/(Ca+Fe+Mg) ±5% Fe/(Ca+Fe+Mg) ±10%	Should be updated with more precise analytical techniques
Olivine	Compositional variations only defined accurately for transmission spectra	Derive Mg/(Fe+Mg)
Plagioclase	Strength of plagioclase band is known to depend on FeO content	Resolve ambiguity between abundance and FeO content Derive FeO content of feldspar
Glass	Absorption characterictics of Fe and Ti bearing glasses have been measured for terrestrial and lunar materials	Calibrate Fe, Ti variations for reflectance spectra Understand vitrification and devitrification processes and products for various surface environments Understand conditions and variations of impact melt
Oxides	Much is known about absorption characteristics of crystalline and amorphous iron oxides; the conditions under which they are produced have been investigated, but are not well understood	Determine the proportions of mixtures of amorphous and crystalline iron oxides Determine the conditions under which they are developed

Alteration Products on Planetary Bodies	Status	Goals
Moon	Complex glass-welded aggregates (agglutinates) are the principal alteration products of the regolith TiO_2 content can be estimated for mature mare soils to ±2% (±1% relative)	Determine the effects of shock on mineral properties Distinguish breccias, impact melt, and lithic assemblages Estimate FeO content of mature soils Estimate Fe and Ti content of pyroclastic glasses
Mars	Global dust is fine-grained ($<10\ \mu$) weathering product of mafic silicates	Determine the nature and origin of global dust Determine the sources, sinks, and distribution of global dust Clarify the sulfate-bearing minerals and delineate water or hydrated minerals in the permafrost General mineralogy (acidic - basic) of volcanic flows)
Asteroids	Fine-grained regolith exists. Its nature is unknown, but the presence of significant agglutinates is not expected	Determine alteration products of the radiation and impact environment on asteroid surfaces
Outer Satellites	Regolith contains fine-grained frosts	Determine the effects of irradiation (ion, ultraviolet, etc.) and vacuum weathering Determine the effects of cumulative impact processes (macro and micro) Determine the nature (meteorite, cometary) of the impacting material in the outer solar system Determine the minor components (clathrates and hydrates) in water frost surfaces

Table 4. The Role of University and Government Centers in Reflectance Spectroscopy

Center	Contribution
University of Arizona	Measurement of transmission and reflectance spectra of frozen volatiles for application to outer solar system problems Derivation of absorption coefficients
Brown University	Bidirectional reflectance measurements of lunar and terrestrial materials Deconvolution of mineral mixtures Acquisition and analysis of telescopic spectra for unexplored lunar areas Investigation of regolith development on lunar and asteroid surfaces Analysis of venusian surface spectra
Cornell University	Phase function studies of spacecraft data Laboratory phase function measurements
Goddard Space Flight Center	Infrared spectroscopy on megaelectronvolt irradiated samples of low temperature comet-ice mixtures
Hawaii Institute for Geophysics, University of Hawaii	Development of advanced mapping and point spectrometer instruments and analysis software systems, especially for spectrum and image cube data processing Acquisition and analysis of telescopic spectra of Mercury, Moon, Mars, outer satellites, and asteroids Bidirectional reflectance measurements of analog materials including silicates, metals, and volatiles under a wide variety of environmental conditions Implantation of S and SO_2 Spectrum database management and networking
Jet Propulsion Laboratory	Development of analysis software for mapping spectrometer data Acquisition and analysis of telescopic spectra for asteroids, outer satellites, and atmospheric clouds Spectrogoniometric and diffuse reflectance measurements of sulfur, frosts, and mixtures of minerals and ices Proton and ultraviolet irradiation of minerals, rocks, sulfur, and ices Theoretical analysis of phase functions
Johnson Space Center	Bidirectional reflectance measurements of Mars analog materials with a focus on the properties of iron oxides and oxyhydroxides Acquisition and analysis of reflectance spectra of asteroids and Mercury
University of Massachusetts	Development of automatic analysis capabilities, including extraction of absorption band information from reflectance spectra Weathering processes on Mars
University of Maryland	Acquisition and analysis of asteroid and comet spectra
Massachusetts Institute of Technology	Spectral measurements of minerals, glasses, colloids, and mixtures of these (100-600 K) Theoretical calculations of molecular orbital energy levels to aid assignment of energies and intensities of spectral features observed in reflectance spectra
University of Pittsburgh	Develop reflectance spectroscopy theory Application and testing of theory for planetary data (Moon, Mercury, asteroids, satellites) Supportive laboratory studies Effects of melting, vaporization and kiloelectronvolt ion irradiation on optical properties of minerals
Rensselaer Polytechnic Institute	Derivation of interpretive spectral calibrations appropriate for asteroids for investigations of the thermal and collisional evolution of the early planetesimal population Acquisition and analysis of time varying (rotational) asteroid spectra Determination of the fundamental properties of carbonate spectra
U.S. Geological Survey (Denver)	Development of fast algorithms to derive mineral abundance and grain size information using reflectance theory and optical constant information Analysis of icy satellite spectra
U.S. Geological Survey (Flagstaff)	Multispectral image data analysis and map making Development of computer data processing software systems and techniques for multispectral image analysis and cartography

Table 4. The Role of University and Government Centers in Reflectance Spectroscopy (continued)

Center	Contribution
University of Virginia	Kiloelectronvolt ion irradiation of low temperature condensed gases Materials analysis, including infrared spectroscopy Megaelectronvolt ion work in conjunction with AT&T Bell Labs
Washington University	Efficient management of imaging spectrometer data
University of Washington	Merging of reflectance spectrophotometry with multispectral imaging Development of algorithms to compare image spectra with laboratory reference spectra Development of spectral mixing models that cover composition, particle size, and lighting geometry variations
University of Wyoming	Development of analytical models for complex mixtures

Table 5. Facilities for Obtaining Planetary Reflectance Spectra

Location	λ range(μ)	λ resolution	Comments
Telescopes			
HIG	0.35-1.0	1.5%	Circular variable filter
HIG	0.6-2.6	1.5	Circular variable filter
HIG	2.0-5.0	1.5-3.0	Circular variable filter
HIG	1.0-5.0	<~1%	Grating imaging spectrometer (being tested)
UA	0.3-2.5	? High	Interferometer
UA	0.3-1.0	? High	CCD; grating spectrometer
IRTF	0.8-5.0	~3%	Circular variable filter
IRTF	1.0-5.0	~1-1/3%	Grating array
McD	0.3-1.0	1%	CCD; grating spectrometer
possible future:			
JPL/IFA	1.0-2.5	1/2%	Prism spectrometer (proposed)
HIG	0.2-5.0	<~1%	Grating imaging spectrometer (augmentation of above device under way)
Spacecraft			
IUE	0.1-0.3	High	Grating spectrometer
Galileo	0.7-4.0	0.5%	Scheduled to fly 1989 or 1991; will measure satellites of Jupiter as well as asteroid (flyby); data in 1 to 5 years after launch
Mars Observer	0.35-4.3 or 5	~1%	Scheduled to fly 1990; data in 1991/92
Lunar Geochemical Observer			Mapping spectrometer being planned; mission anticipated; data in 1992/3
Comet Rendezvous/Asteroid Flyby			Spectrometer being planned; mission anticipated; data in mid-1990s
Space Telescope	0.1-0.7	High	High resolution grating spectrometer

Abbreviations:

HIG	Hawaii Institute for Geophysics, University of Hawaii
UA	University of Arizona
IFA	Institute for Astronomy, University of Hawaii
IRTF	NASA Infrared Telescope Facility, Mauna Kea Observatory, Hawaii
JPL	Jet Propulsion Laboratory
McD	McDonald Observatory, University of Texas

Table 6. Facilities for Laboratory Spectral Reflectance Measurements

Institution	Instrument		λRange		λ Resolution (nm; visible)	λSampling (nm)	Sample Orientation[3]	Environment Control[4]	Irradiation Facility[5]	Analytical Facilities[6]	Special Features[7]	Upgrade[8]	
	Type[1]	Model[2]	Start	End								In Progress	Planned
University of Arizona	Bi-?	Idea IH	1.0 0.4	-5.0 -1.0	0.2 1	0.1 0.5	VT-C	LT, V			a	Repair	
Brown University	Bi@-D	IH:Relab	0.35	-2.6	1.6	1	Hz-U	HT		P, X	b,c		A,C,F
Cornell University	Bi@-D	IH	0.35	1.2	10	10	Hz-U					K	
Goddard Space Flight Center	Bi	PE	3.3	-27	3/30	1	VT	LT, HT, V, G	M		e		
Hawaii Institute of Geophysics	Bi@-D	IH	0.35	-5.0	< ~1%	< ~1%	Hz-U	LT, HT, V, G		P, X	a,b	B,I	
Jet Propulsion Laboratory	Hm-A Bi-A Bi@ Bi	B-DK2A Act IH A	0.25 0.23 VIS 2.3	-2.5 -6.0 -22	~1% ~1% 2 cm^{-1}		V-C Hz-U Hz-U Hz-U	LH, HT, V	K, UV	X, S		C,D,E	
Johnson Space Center	Hm-D Bi@-D	Ca14 GW	0.2	2.5	0.1 2		Hz-U Any	LT,HT	UV	P,X,M, S,T,I, V			J
University of Massachusetts	Hm-D	PE	0.35	2.5	~1%	~1%	Hz-C		UV			D	
Massachusetts Institute of Technology	Hm-A	Ca17	0.3	2.2	1	1	Hz-U	HT		P,X,M			D,G
University of Pittsburgh	Bi-A Bi@-A	Ca14 IH	0.2 VIS	2.5 VIS	0.1 10	0.1 ~70	Hz-U Hz-U	LT LT	K, UV, X	X,S	b,c	D	
Rensselaer Polytechnic Institute										P,X,S,F,A			
U.S. Geological Survey (Denver)	Hm-D Bi@-D	B5270 N	0.2 1.6	4.0 20	0.05-32 0.2-40	0.05-32 0.2-40	Hz-U	LT, HT, V, G		P,X,S,D,F	b		
University of Virginia	Bi@-D		2.1	5.0	1/20	(FFT)	Vt	LT, V, G	K, M	X,S,SI	e		
University of Washington	Hm-D	B-DK2A	0.35	2.5	0.2-2.2	0.2-2.2	V-C, Hz-U	LT, HT, V, G		P,X,S			

[1] Bi, bidirection reflectance
@, plus full angular control
Hm, hemispheric (diffuse reflectance)
D, digital output
A, analog output

[2] IH, built in house
Ca, Cary
PE, Perkin Elmer
B, Beckman
A, Analect
N, Nickolet
GW, Guided Wave

[3] Hz, horizontal
Vt, vertical
U, uncovered
C, cover glass used

[4] LT, low temperature
HT, high temperature
V, vacuum
G, gas mixing

[5] K, keV ions
M, MeV ions
X, x-ray
UV, ultraviolet
G, gamma ray

[6] P, microprobe
X, x-ray diffraction
M, Mossbauer
S, SEM
T, TEM
F, x-ray flourescence
E, Esca
A, Auger
SI, SIMS
I, instrumental neutron activation analysis
V, vibrating sample magnetometer

[7] a, same instrument as that on telescopes
b, can precisely measure small samples (20-100 mg; 1 mm clasts)
c, polarization optics
d, UV/visible flourescence spectral capability
e, ion beam attached to environment chamber

[8] A, spectral range extended to ~5 μ
B, spectral range extended to ultraviolet
C, environment chamber
D, output digitized
E, optics for polarization measurements
F, camera to record state of sample
G, high pressure spectra (diamond cells)
H, atmosphere control chamber
I, increase spectral resolution to ~1/4%
J, ultra-low (1.2 K) temperatures
K, small phase angles

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Table 7. Computer Facilities and Personnel Involved in Spectral Analysis

Location	Hardware: Spectra analysis	Hardware: Image processing	Operating System	No. of Scientists	No. of Students
University of Arizona	Hp 9000	Vicom		2	2
Brown University	Micro Vax II	Vax(DEC) 750	VMS	1	1
Cornell University	Vax(DEC) 750	Vax(Dec) 750		2	2
University of Hawaii	Vax(DEC) 750	Vax(DEC) 750 SUN 3/IIs	UNIX/VMS	5	7
Jet Propulsion Laboratory	Vax(DEC) LSI	Vax(DEC)	VMS/UNIX	3	
Johnson Space Center	IBM pc Vax(DEC)	Gould	MS-DOS/VMS	2	1
University of Massachusetts	Hewlett Packard			1	
University of Maryland	IBM pc		MS-DOS	2	
Massachusetts Institute of Technology	PDP 11/73			1	2
University of Pittsburgh	IBM pc		MS-DOS	1	1
Rensselaer Polytechnic Institute	IBM pc		IBM-DOS	1	
U.S. Geological Survey (Denver)	Hp 9000 Vax (DEC)	Pe 3240 Vax (DEC)	UNIX/VMS	3	
U.S. Geological Survey (Flagstaff)				2	
University of Virginia				1	
Washington University		Vax (DEC) Micro Vax II	VMS	1	
University of Washington	Symbolic	Symbolic	VMS/UNIX	2	
University of Wyoming	Cyber		NOS	1	

Chapter 6

Future Applications and Requirements

Missions

Future planetary missions will rely heavily on spectral reflectance and spectral imaging experiments. Because of the immense data return expected from these missions in the next two decades, a new era will begin in qualitative and quantitative analysis of spectral reflectance data.

NASA has emphasized the major role reflectance spectroscopy will play in the solar system exploration program by making the visible and infrared imaging spectrometer instrument (VIMS) a facility instrument for all missions starting with the Mars Observer. Major support is required for the reflectance spectroscopy field in order to make the experiment results match the prominence in the payloads.

It appears that competing solar system exploration programs in other countries will also include reflectance spectrometer experiments, further increasing the need for an understanding of the techniques and science of the field.

The major missions likely to carry reflectance spectroscopic investigations are listed here in approximate chronological order of data return.

Phobos - Soviet mission to Mars with emphasis on studies of the satellite Phobos, will probably carry French infrared spectrometer similar to Vega instrumentation and multispectral CCD imaging. Launch, 1988; Mars data return, 1990.

Mars Observer Mission (MOM) — U.S. mission to orbit and map Mars, will carry a visible and near infrared mapping spectrometer system. Launch, 1990; Mars data return, 1991.

Galileo — U.S. mission to Jupiter with extensive studies of the planet and satellites, will carry multispectral CCD imaging and a near infrared imaging spectrometer (NIMS). Will probably fly by one or more asteroids in addition to Jupiter mission. Launch, 1989; data return at Jupiter, 1994; asteroid data return, 1990 (?) and 1992 (?).

Soviet Lunar Polar Orbiter — Soviet lunar mission with infrared spectral reflectance capability. Launch, early 1991 (?); data return 1992 (?)

Lunar Geosciences Observer — U.S. lunar mission, similar to MOM. Launch, early 1992 (?); data return, 1992 (?).

Vesta — Soviet/French mission to Mars with separate spacecraft going to one or more asteroids; will probably carry infrared spectrometers on both Mars and asteriod 1994 (?).

Comet Rendezvous/Asteroid Flyby (CRAF) — U.S. mission to an asteroid and comet nucleus, will carry a visible and near infrared reflectance spectrometer with mapping capability. Launch, 1992 (?); arrival at comet, mid-1990s.

Cassini — U.S./ESA mission to Saturn and Titan, will orbit and study rings and satellites as well as Saturn and Titan. Cassini will probably also fly by an asteroid en route. Recommended payload includes visible and near infrared spectral mapping experiments on the orbiter and some near infrared spectral and/or imaging system on the Titan probe. Launch, mid-1990s (?); arrival at Saturn, ~2002 (?).

Major Scientific Issues and Questions

Analysis of the current planetary reflectance spectroscopy data sets (which are almost totally telescopic), plans for future telescopic work, and preparation for the upcoming spacecraft experiments point to a number of major scientific problem areas that are the focus of much of the current work in the field. The following sections indicate current broad research trends.

Icy surfaces/frozen volatiles

One major new area of investigation made possible by recent advances in spectroscopic instrumentation and theory is the search for volatiles such as NH_3, CH_4, and CO on the surfaces of icy satellites. Because most of these volatiles, if they occur on satellite surfaces, probably exist in small quantities and in clathrate or hydrate form, the required data and spectral analysis capabilities have not existed until recently. This is an important new area of spectral investigation because the results are necessary for understanding the conditions of satellite formation and the important drivers for their subsequent geophysical, geochemical, and geological evolution. At the temperatures of most of the satellites, normal H_2O ice is a reasonably strong rock, and the observed geological activity on many icy bodies is probably facilitated by the presence of these non-water condensables.

Dark material in the solar system

Low albedo material ($p \sim 3$-10%) is a major component of many bodies in the solar system. The surfaces of Mercury and the Moon are composed basically of silicates which are intrinsically relatively dark and are further darkened by soil maturation processes. The dark materials on the satellites of Mars, many asteroids, outer plant satellites, some planetary rings, and comet nuclei have very different spectral properties from the lunar soils and are believed to be carbonaceous in nature. The relationship of this material to the dark carbonaceous meteorites, the differences among the several types of dark objects known, and the origin of this material (whether primordial or produced by irradiation of carbon-rich ices or some combination of both) are open questions and are or should be the subject of intensive study using spectral techniques.

Asteroidal materials

Of the eight missions listed above, five may obtain spectral data for asteroids. These missions will be the first to these very important objects. Asteroids provide a window on the early processes of condensation and accretion which are obscured by later events on planetary-sized bodies. Major gaps remain in our ability to interpret the data expected from these missions.

Reflectance spectroscopy results from telescopic studies suggest that a major fraction of inner-belt asteroids are metal-rich objects (perhaps analogous to the pallasite and lodranite meteorites). Chondritic asteroids would also have a metal component in their regolith, but derived from discrete gains in the bedrock rather than from the fracture of large metal masses. Laboratory spectra of these meteorites have not been obtained yet because of the extreme difficulty in producing a realistic metal-rich regolith simulation from solid meteoritic NeFe alloy. There is little information about how impact gardening affects a material whose components have radically different mechanical properties, since the terrestrial planet surfaces do not have any such materials. To properly interpret spectra of asteroid areas returned by these missions, a detailed knowledge of the physical nature and spectral properties of metal-silicate regoliths (derived from both chondritic and differentiated substrates) is needed. Such knowledge will require an integrated study of mechanical properties, measurements, impact simulation experiments, regolith gardening models, and spectral measurements to derive calibrations of metal/silicate ratios for use in analysis of spacecraft data.

Mars mafic mineralogy and interior composition

The mineralogy of the volcanic flows and other features on Mars is a good indicator of the thermodynamic and chemical conditions under which these features and their composite material formed. Since they are derived from the Mars interior and at different times in the evolution of the planet, they are a useful probe into the evolution processes. A quick study of Mars surface morphology using images shows many volcanic features, including large shield volcanos and extensive flows from different eras. Volcanism played a major role in the evolution of Mars. Existing Mars reflectance spectra show the presence of pyroxene and possibly olivine as well as the weather products (amorphous iron oxide) of volcanic glass. Just recently, telescopic instrumentation has begun to resolve spatially, with high signal to noise and broad spectral coverage, the major volcanos and volcanic regional units on Mars. Future Mars-Earth oppositions should enable us to increase our knowledge of the mineralogy of these units. This knowledge, with estimates of the time sequence of feature implacement, should help constrain models of the interior evolution of Mars.

Salts on Mars and volatile evolution

Extensive evidence of catastrophic surface flooding on Mars, indicating huge aquifers, together with evidence for extensive hard frozen permafrost which could be intruded by igneous bodies, suggests the possibility of brine development and stabilization during Mars' history. There is also direct Viking-observed evidence for salt cementation (the soil-capping "duricrust") at the landing sites which may be even better developed elsewhere on Mars. Finally, many models suggest an early CO_2 greenhouse which would require subsequent formation of large carbonate deposits to "hide" the CO_2 in the regolith. Thus the search for salts is of primary interest for the MO mission. The best hope is to identify prominent infrared absorptions for the anion groups in sulfates, carbonates, and nitrates in the 3—5 μ range and secondary bands at shorter wavelengths. However, extensive laboratory work is needed in which spectra to 4.5—5.0 μ are measured of trace or minor amounts of these infrared-active salts mixed with likely matrix material (like palagonite) thought to constitute the bulk of the regolith. Such work has not yet been performed but the results would be highly supportive of one of the major Mars Observer Mission goals.

Lunar basins and early crustal development

The major impact basins on the lunar surface have excavated material from a variety of depths and deposited this material in a systematic manner around the impact site. Analysis and interpretation of spectra obtained from these deposits provide key information concerning the composition and stratigraphy of the lunar crust in the pre-impact target sites. Comparison of the results for different basins will lead to a better understanding of lateral variations in crustal composition. Spectral data for distal basin deposits can be used to determine the importance of "local mixing" by secondary cratering processes and to help place the returned lunar samples in their proper regional context.

Sulfur and sodium chemistry and mineralogy on Io and Europa, and magnetospheric effects on the Galilean satellites

Sulfur and sulfur compounds are thought to be ubiquitous in the inner jovian satellite system. These materials, which are produced on Io, are spread throughout the jovian system by the powerful jovian magnetosphere. In the most general sense, the major issues that spectral reflectance properties can address include: (1) what is the nature of the spectrally active materials on the surface of Io? (2) what relationship does this material have to the crust of Io? (3) how are these materials formed? and (4) what effects do these materials, once captured into the jovian magnetosphere, have on the spectral reflectance properties of the other jovian satellites (namely, Europa and Amalthea)?

Spectral reflectance properties of these satellites have been investigated on both global (ground-based telescopic and Voyager 1 and 2) and regional (Voyager 1 and 2) scales. Data exist for studies on local scales, but little has been done. Laboratory spectral reflectance properties of sulfur and sulfur-related compounds are required if the issue of sulfur versus silicate (basalt) landforms on Io is to be addressed correctly. Similarly, laboratory studies of materials in simulated jovian environments (i.e., radiation, thermal cycling, etc.) must be attempted before we understand what happens on local and microscopic scales to form and modify the surfaces of Io, Europa, and Amalthea. Ion implantation into ice and silicate materials is a relatively unexplored area in the context of spectral reflectance measurements. These studies will have particular relevance to Europa, Ganymede, and Amalthea.

Surface Modification

A major problem for geologists trying to understand the surface composition of solar system objects has been the various surface alteration processes. These are often interesting in themselves. Also, knowledge of processing (weathering) rates for surface materials can give information on the age of soil and rate of turn-over of crustal materials. A simple example is the amorphous layer produced on lunar materials exposed to solar wind bombardment which indicated that a particular material in an Apollo sample was indeed on the surface (i.e., weathered) at some time. Of course, knowledge of the very active weathering rates on Earth is an important geologic tool. The weathering processes also indicate much about the environment experienced now and in the past.

Weathering can also play a role in obscuring the primary mineral composition of the surface. There are many interesting and important problems in this area, for example, hydroxalization and oxidation of Mars surface materials. The effects of weathering vary; some planetary bodies have (had) atmospheric and fluid envelopes, and some are rock with essentially no atmosphere, such as the Moon, Mercury, and the asteroids. These may be modified by meteoritic, solar, and galactic particle bombardment and possibly by ultraviolet irradiation. In fact, the recent evidence for sodium sputtering on Mercury may help increase our understanding of that surface.

The surfaces of the small bodies and grains in the outer solar system, particularly those orbiting within magnetospheres, have been irradiated at a variety of levels early in their formation and are being irradiated at present. Because these surfaces are composed of volatile materials, the irradiation effects are correspondingly much more dramatic than those produced in the rocky objects in the inner solar system. For example, condensed volatile materials can be directly converted to organic materials and organics to highly carbonized (dark) materials by particle radiation. In addition, particle radiation has been shown to compete with sublimation in determining the grain sizes of the icy regoliths of outer solar system bodies and clearly competes in determining the crystallinity of the volatile layer. As the penetration depths of the incident radiation are often comparable to the sampling depths of the reflected photons, the effects of such weathering will be evident in the wavelength region of interest. Therefore, reflectance spectra can give information on the active weathering of these surfaces as well as on the important question of whether or not the obscured materials are primordial.

Planet Surface Mineralogy and Processes

Determination of the mineralogies of altered and unaltered primary rocks and how they vary across a planet's surface is a major goal of reflectance spectroscopy. Indeed, the technique is the only one available for globally mapping mineralogy. All the terrestrial planets appear to have undergone differentiation into crust, mantle, and core. Primary rock mineralogy provides direct clues to the composition of these basic global components and the nature of their implacement. We know that Earth has a granodioritic crust and that the Moon has an anorthositic crust. The compositions of the mercurian and martian crusts are unknown, but they can be determined from the mineralogies of rocks of the cratered unplands or of crustally derived volcanic rocks. Of particular interest for models of accretion of Mars is the extent to which hydrated minerals such as amphiboles and micas are present. Similarly, the mineralogy of volcanic rocks provides direct clues about such fundamental mantle properties as oxidation state, Fe/Mg ratio, and Ti content. In addition, layering in the upper mantle can be inferred from the different mineralogies of differently aged rocks, as determined by crater-counting studies.

Knowledge of the variability of volcanic mineralogy wil lead directly to a better understanding of volcanic processes. Reflectance spectroscopy may, for example, reveal that different volcanic landforms, such as shield volcanos, paterae and lava plains, and volcanic provinces such as Tharsis and Elysium, are compositionally distinct. Most volcanism on planets other than Earth appears to be basaltic. A wide variety of products that result from interaction of lava and groundwater or ground ice may be present where more siliceous forms of volcanism dominate.

We must achieve a better understanding of the mineralogy of primary and secondary (weathered) alteration products on Mars. Abundant chemically altered weathered products appear to be present, but it is not clear when and under what climatic or environmental conditions these products were produced. Knowledge of the mineralogy of the weathered products, as provided by spectroscopy, will greatly help us understand these problems. Detection of salts such as sulfates, carbonates, and nitrates will also help us understand not only the source of the weathered debris and the sink for volatiles but also the climatic conditions under which transport and segregation of the products took place.

Scientific questions concerning the Moon and asteroids that will be addressed by reflectance spectroscopy are more sophisticated because of the availability of samples which can be studied in the laboratory and used to model components of an unexplored surface. Reflectance spectroscopy is particulary effective here because the lunar and meteorite samples provide compositional information that ties the remote measurements with reality in a very direct way (i.e., groundtruth), and it provides not only scientific results but also technique verification and development.

It seems likely that new assemblages and new components will be discovered with spacecraft measurements of the Moon and asteroids. For example, a variety of pristine crustal materials have been identified as fragments in the lunar sample collection; their lateral and vertical distribution is unknown, but fundamental questions about the formation and evolution of the lunar crust depend on this information. For the Moon, the high spatial resolution spectra expected from an orbiting satellite will allow extensive details of crustal stratigraphy to be examined locally (largely through measurements of the material excavated by large and small impact craters) and globally (through measurements associated with a variety of major basins). Primary requirements to obtain the desired scientific information from such studies include developing a detailed understanding of the spectral character of key lunar materials and the effects of shock metamorphism and brecciation as well as the deconvolution of complex multicomponent lunar spectra to produce accurate measurements of mineral abundances.

Asteroid science has similar requirements (laboratory mesurements of key meteorite materials, examination of alteration effects, and accurate analytical techniques). The questions are, of course, quite different and relate to distinguishing the nature and extent of the earliest differentiation events in the solar system. A major question is whether some asteroids are extinct comets or whether cometary nuclei are like asteroids. Visible and infrared spectroscopy will be a primary tool in addressing this question with future Earth-based and spacecraft observations (e.g., CRAF).

For Mercury, a major question is whether there is any ferrous iron at the surface, and if so, in what mineral(s). If not, is the surface highly reduced? The sodium detected in the atmosphere presumably is sputtered from the surface, implying the presence of an Na-bearing mineral in the regolith. This presents a puzzle because Mercury is thought to have formed under high temperature conditions that would not have been favorable for retention of large amounts of sodium.

Near-Earth asteroids are particularly interesting because they are near Earth and may account for a large share of the meteorites. Some investigators believe that these objects contain a population of extinct comet nuclei. Others argue from existing spectral reflectance data that all these objects can be explained by mineral assemblages like the main belt asteroids and that they are derived from that source, expecially near the 3:5 resonance. Continued telescopic observations and a low-cost spacecraft rendezvous will determine more completely the suite of mineral assemblages composing this group of objects and answer the question of their ultimate origin.

Outer planet satellites pose other challenges. Icy bodies present water ice and clathrate mineralogies which must be identified. Water volcanism or other resurfacing processes are possible. Io is a most active volcanic environment, with flows, plumes, and calderas, but even the major type of volcanism (silicate, sulfur) and the effects of the vacuum environment on material properties are not well described. The Galileo NIMS investigation and further ground-based observations will present important data sets for interpretation.

Techniques and Data Required

In order to address the scientific questions described above and to prepare for the analysis of spacecraft data in the near future, considerable effort in a number of areas is required. Again, this discussion is meant to be illustrative and not exhaustive.

Theoretical work

The physical and chemical principles and the general basis for understanding and interpreting reflection spectra have been brought to a reasonably mature level in the last two decades. The effort can be thought of as having three components: (1) identifying the presence of specific minerals, (2) making quantitive estimates of phase chemistry, and (3) determining the relative abundance of the phases. The latter two are more difficult and require better models. The effort required in these areas includes work aimed at understanding the effects of temperature and the physical state of the surface on spectrophotometric properties.

Underlying the application of reflectance spectroscopic data in planetary sciences is the correct assignment of observed spectral features. This is achieved in large measure by direct measurements in the laboratory of candidate minerals and mineral assemblages (rock types) believed to comprise materials on weathered or irradiated planetary surfaces. However, the ultimate assignment of band energies and intensities is based on calculated energy levels and transition probabilities. As molecular orbital calculations (requiring huge computing capabilities) become more sophisticated, necessitating considerations of next-nearest neighbor and other environmental interactions (variable ligands, point defects, broken bonds at crystal surfaces), so too will the precision of interpreting reflectance spectra evolve. The special properties that planetary materials have provided (Fe and Ti in lunar glasses, Ti^{3+} and $Fe^{2+} \rightarrow Ti^{4+}$ spectral features in lunar minerals, poorly crystalline martian Fe^{3+} oxides and clay silicates) have yielded problems unique to planetary science. Such leading-edge fundamental scientific research must continue to be carried out.

Particularly important are mathematical models relating fundamental material properties (such as the complex index of refraction) to the diffuse reflection spectrum of a realistic planetary surface composed of such materials. This allows measurements of spectra of end members of material compositions and mixtures in the laboratory to be used to calculate spectra of a multitude of mixtures and gradations of these materials and reduces the need for more expensive and time-consuming laboratory measurements. This is a complicated problem because of the multiscattering environment among grains of differing size, shape, and optical properties. A particular problem is the case of mineral mixtures and the methods for deconvolving the mixture spectra. Models exist, but they must be made more sophisticated and easier to use.

Several specific requirements can be identified in this area:

Continue to develop a mathematical model for calculating the diffuse bi-reflectance spectrum for mixtures of materials using the optical constants of end members.

Continue to provide the association of specific bands with the chemical nature of the materials.

Continue to develop models for deconvolving the spectrum of mixtures of materials and derive the end member materials and their relative contributions.

Develop models for separating the atmosphere from the ground for Mars observations.

Telescopic observations (gound based and Earth orbital)

Essentially all data obtained for solar system objects have come from ground-based telescopic observations. While more and more data will come from the missions described in the beginning of this section, telescopic studies will remain a critical element of planetary reflectance spectroscopy for a number of reasons:

Some bodies, particularly in the outer solar system, will not be visited by planetary missions until well into the next century.

Telescopic studies will be used to supplement and support missions, providing time and spectral coverage unavailable to the spacecraft experiment and/or data bases on other similar objects to provide the context for spacecraft measurements (e.g., for asteroids and comets).

Telescopic observations (and Earth observations) will remain the proving ground for new instrumentation and techniques, since spacecraft experiments must by nature use tried and (by the time of encounter) usually out-of-date methods.

Future requirements to maintain and advance the knowledge and technique base in reflectance spectroscopy as applied to planetary science include:

Support the ground-based telescope facilities required for the measurements. The most actively used facilities include the NASA IRTF and the University of Hawaii 2.2 m telescopes on Mauna Kea. The JPL Table Mountain observatory, McDonald Observatory, and Kitt Peak telescopes have been used as well. The current pressure for observing time is illustrated by the fact that observing time on the IRTF is oversubscribed by a factor of 3 for the current observing period (fall 1986)

Support the modification of existing and the development of new array spectrometers to reach fainter objects, obtain better precision over a wider spectral range, particularly in the 1.0 — 5.0 μ spectral region, and produce data sets which simulate those to be obtained by space missions.

Provide better support in general for facility maintenance and provide better support for guest investigators to use existing equipment and telescopes.

Provide for the restoration to a common format of the existing data sets; they are difficult or impossible to duplicate. These data sets should be placed in the Planetary Data System as part of the reflectance spectroscopy node responsibilities.

A problem in this area is that the ground-based observing program is supported by a separate program within the Solar System Exploration Division other than the Planetary Geology and Geophysics Program. Closer coordination is required between these two programs.

Laboratory measurements

Laboratory measurements have increased in the past 5 years as several new research centers have developed. This is in response to the greater demand for such data. The existing data sets, especially the earlier sets, are not well documented and have not been restored to a common format. Some are on tapes that are difficult to read. This kind of information will be in demand in the future.

Continued laboratory work aimed at addressing some of the problems discussed above is required to provide a sound interpretive base for both mission and telescopic work. This work should focus on obtaining a detailed understanding of the physical and chemical processes that affect spectral information in the environment of actual planetary surfaces; these environments differ greatly from object to object. The development of appropriate and well-characterized data bases of spectroscopic information is a part of this effort, but this should not consist of simply building large reference libraries of spectra. It is equally important to obtain an accurate analytical capability to extract the desired information from complex multicomponent spectra. Among the requirements are

Environmentally controlled studies of candidate planetary volatiles

More information about the mid-infrared range, from 2.5 to 50 μ

Studies aimed at unraveling various forms of spectral mixing

Studies of the effects of sample temperature on spectra

Environmentally controlled studies of salts and hydrated minerals, including during hydration and dehyration

Radiation bombardment of particulate media rather than smooth, flat surfaces, and particularly of ices, so that processes in a regolith are simulated realistically

Studies of optical properties of crystalline phases having sub x-ray dimensions

Better characterization (chemical, phase, grain size, etc.) of samples upon which spectral measurements are made

Imaging spectroscopy

One of the most important trends in the field of remote sensing is the development of spectral imaging systems which produce large, two-dimensional arrays of moderate to high resolution spectra—"images"—for which each picture element is associated with a full spectrum, not just a few broadband colors. These data sets are often called image cubes. Virtually all U.S. planetary missions in the future will carry devices of this sort, and a number of Earth-orbital spectral imaging experiments will have been flown (indeed, terrestrial applications are providing one of the strongest drivers for the development of these techniques).

These developments will have a profound effect on the field of reflectance spectroscopy and pose a number of formidable challenges to researchers. As the field moves from the "classical" mode of single spectrum analysis to manipulation of massive ($>10^8$ to 10^{11} bits) data sets, new methods will have to be developed for preparing, assimilating, and analyzing these data. The scale of this problem may be illustrated by considering that there are now perhaps about 1000 visible to near infrared spectra of individual planetary bodies (mostly for lunar areas and individual asteroids) or different parts of their surfaces; the Galileo NIMS experiment will exceed this data volume in its first 25 minutes of operation! One major challenge is simply preparing the spacecraft data set in a form which is useful for further detailed analysis; the experiments will not in general produce simple, error-free, geometrically pure data bases, and the production of geometrically accurate, well-sampled data bases with spacecraft and lighting geometry effects removed will be a major task. Learning to organize and extract the geochemically and geologically most useful information from these data bases will require a major research effort as well, combining mathematical tools for data handling, laboratory and theoretical analysis, and correlations with other data sets.

Work is currently being carried out in many of the areas mentioned above, but far more must be done to prepare for the data expected in the next 10 years. In the very near future, workers in remote sensing will deal with increasingly unified mixtures of spatial and spectral information and will often be presented with spectra in an imaging context and images as collections of spectra. Some suggested areas of emphasis are

- Continue to develop and distribute integrated software data processing systems such as GARP and SPAM for the routine handling of image cube data sets in coordination with space mission projects such as Galileo and MOM, for which such development is also needed.
- Develop innovative approaches for analyzing image cube data sets using expert systems and artificial intelligence technology to extend the scientists' capability.
- Promote research projects which will test and motivate these capabilities.

Chapter 7

Strategy and Implementation

Scope of Program and Approach

The scope of the reflectance spectroscopy program is extremely broad. The program encompasses all objects in the solar system and involves many disciplines other than spectroscopy, such as geology, geochemistry, geophysics, and atmospheric science. The nature of the program is documented in previous chapters. Here we emphasize that a broad scope of effort requires a careful balance among several areas of research in order to be effective. These include:

- Theory and technique of reflectance spectroscopy
- Laboratory studies of candidate materials
- Analysis and interpretation of existing planetary data
- Acquisition of new telescopic data
- Planning and preparation for spacecraft missions
- Participation in missions and in post-mission data analysis and interpretation

These areas of research are so closely interwoven that the strength of the program depends on maintaining a balanced effort that covers all areas. For example, further development of background theory is of paramount importance at this time in preparation for upcoming spacecraft missions which will require entirely new methods of spectral analysis. In addition, new telescopic data will not only produce important new discoveries, but will be an important high-spectral resolution supplement to future spacecraft data from, for example, Galileo NIMS.

Any implementation of the program must take into account the problem of establishing a long-term perspective and a continuity of effort. Future NASA and foreign spacecraft missions are primarily oriented toward remote sensing experiments (in contrast to landed experiments or sample return), and reflectance spectroscopy is an essential part of most payloads. In an era of budget awareness and post-Challenger rescheduling, the missions that once appeared imminent are now likely to be postponed. It will be a major challenge to maintain and develop an innovative and forward-looking program in an era of mission delays and uncertainty. However, without this continuity the hard-won missions may be compromised by lack of preparation, reducing the potential for reflectance spectroscopy to play a key role in future planetary science discoveries.

Program Focus

Certain aspects of the reflectance spectroscopy program urgently require attention if mission objectives and science objectives are to be met. These include critical research problems and other problems that are largely programmatic in nature. More detailed discussions of some of these problems and proposed solutions appear in later sections of this chapter.

Mission Readiness

Planetary reflectance spectroscopy has its roots in telescopic observations. Telescopic spectra are not easily obtained because of object availability, telescope availability, observing conditions, etc. Even today, high-quality telescopic spectra of planetary objects are numbered in the hundreds. Interpreters have been able to treat spectra on an individual basis and have not had to be concerned with processing large quantities of data.

During the rapid evolution of reflectance spectroscopy over the last 20 years, virtually no spacecraft missions have obtained high-resolution spectra of planetary surfaces. (An exception is the Mariner 6 and 7 IRS experiment in the 1.9—6.0 μ region.) Meanwhile the technology in detectors and in data storage and transmission has surged ahead to the point at which future missions can produce an unprecedented flood of spectroscopic data. Furthermore, the data can be filed and displayed as images. A few tens of seconds of transmission from Galileo NIMS can exceed the total of all of the existing telescopic spectra of the jovian system.

The bulk of future reflectance spectroscopy data from spacecraft cannot be efficiently examined spectrum by spectrum as in the past. An entirely new approach is necessary, one based on a scientific rationale and using new high-speed data processing techniques. New approaches are now being tested in a few laboratories. However, one of our key findings is that *there presently exists an appalling mismatch between the objectives of NASA (and foreign) planetary missions to conduct high data rate reflectance spectroscopy experiments and the present capabilities for data analysis and interpretation.*

We identify below three critical research areas that require immediate attention.

Large data sets and the merging of spectral and image analysis. A crucial aspect of the present mismatch between mission objectives and current capabilities is the problem of managing large data rates from reflectance spectroscopy experiments on spacecraft. This is partly an engineering problem involving data links, data storage, data compression, etc. It is partly a problem at the stage of interpretation, for the scientific community has little experience in working with large data bases; the necessary tools and strategies have not been developed. It is widely agreed that the problem will not be solved by simply increasing computer throughput. It is more likely that the modeling strategies (discussed below) will be used to selectively probe the database, guided by scientific questions.

The appearance of imaging spectrometers has forever changed the nature and scope of reflectance spectroscopy. Future missions will obtain spectroscopic data in the form of image arrays. Multiband images will be treated as spectroscopic arrays. Photogeology and reflectance spectroscopy will converge to provide interpretations that connect compositional information with landforms. Rapid strides are being made in this direction in the NASA terrestrial program using new Airborne Imaging Spectrometer (AIS) data being gathered by JPL.

Images are by nature large data arrays. As the spectral dimension is increased to the range of 100 or more bandpasses, which are necessary for spectroscopic interpretations, the problem of data management becomes acute, as discussed above. It is still common, however, for scientists and program managers to treat spectroscopy and image analysis separately. This division is based on imaging in a few broad bandpasses in past planetary missions and terrestrial Landsat missions. With the advent of imaging spectrometers, the approach to data management must evolve beyond our image-processing techniques. Current standard methods, such as making ratio images and color ratio composites, are of limited use in dealing with hundreds of bandpasses. Although a few research groups are addressing these problems, the level of effort within the planetary reflectance spectroscopy program is low and in fact is declining.

Enabling instrumentation. Two areas require programmatic attention. First, existing laboratory and telescope observing facilities must survive if the mission goals discussed above are to be achieved. Funding must be maintained at a level that allows existing spectrometers and other equipment to operate. Funding for technical personnel is the highest priority in most laboratories, followed by support for maintenance and repair of facilities.

Second, scientific progress depends on new specialized facilities: (1) laboratory equipment to allow spectroscopic measurements of frozen volatiles under conditions such that samples can be characterized by x-ray diffraction and other techniques, and (2) new telescopic instrumentation to allow a 10 to 100-fold increase in sensitivity of spectra of faint objects in the solar system and for small areas on Mars. New facilities such as these might best be run as cooperative efforts.

Predictive spectral modeling. Laboratory reference spectra and reflectance theory together provide the foundation for the interpretation of telescopic and spacecraft reflectance measurements. Advances in both areas within the past 5 years have opened the possibility of accurate prediction of how a spectrum will respond if the measured material is modified in terms of particle size, mixtures with other materials, and changes in lighting geometry. A further objective is the ability to model the spectral effects of atmospheric attenuation and scattering and of instrumental attenuations.

The inverse, the ability to deduce the various components and their condition on a planetary surface from a known spectrum and lighting conditions, is the prime operational objective. It is entirely unrealistic to try to develop a library of reference laboratory spectra covering all possible materials, particle sizes, and possible mixtures. Instead, by measuring the spectra of a relatively few materials under known conditions, other spectra can be calculated using tested algorithms. The difficulty is to make this technique work in reverse: given a photometric-quality spectrum and the lighting geometry, determine the mineral composition and physical state of the surface. The goal of all reflectance spectroscopy and of this approach specifically is the ability to quantitatively determine the phase abundances and physical states of remotely measured materials.

The goal of predictive spectral modeling is realistic in the view of some investigators familiar with recent developments in the field; however, the present level of effort in the program is very modest, partly because technique development is not a high priority of proposal science review committees. Yet an approach like this may well be the only way to analyze efficiently the large quantities of data expected from new missions.

Vulnerability of a Leveraged Program

Attempts to maintain a balanced program with a broad scope in the face of mission delays and constraints on the research budget appear to have resulted in a progressive reduction of support for most indiviudal investigators over the past 5 years, even though new investigators were added and the proportion of the Planetary Geology Program funding for this field was modestly increased. At the same time, the scientific and technical sophistication of the field has increased, thereby increasing the requirements for laboratory facilities, computational facilities, telescopic instrumentation, etc. The program is now highly leveraged, that is, high research output is possible only because other NASA programs, other government agencies, and universities are carrying many of the real costs of planetary reflectance spectroscopy research.

As a simple example of leveraging, consider the investigator whose funding has diminished by some fraction for each of the last 5 years. Five years ago the planetary progam supported a proportionate share of the expenses of running the investigator's laboratory, including technician's salaries, maintenance and repair of equipment, and other costs. As the annual budget diminished, the investigator, reluctant to reduce his or her output in a competitive environment, tried to shift the real costs of operating the facilities to other areas. Another grant that relies on use of a spectrophotometer now supports all of the operational costs. A private foundation and university matching funds are used to purchase a new computer or to replace failed or obsolete equipment.

In the short term, shifting costs to other programs or insititutions appears to be desirable because it results in more research per dollar for the reflectance spectroscopy program. This leverage, however, works both ways, because the control of the program passes to others who do not necessarily share the objectives of the reflectance spectroscopy program. If the other programs default or change direction, the reflectance spectroscopy program is vulnerable.

At present, the reflectance spectroscopy program is highly leveraged in terms of the support of laboratory and observational facilities. Most investigators who do experimental work rely on other sources of support. With further constriction of the progam, we would expect that at some point the demands of the other programs will eclipse planetary reflectance spectroscpy work, and the objectives of a broad and balanced program will be compromised.

Schedule of the Program

The reflectance spectroscopy community recognizes that spacecraft missions are the major drivers for research funding. To a large extent, the present dilemma of shrinking resources is linked to the absence of missions returning or about to return spectral data. Following the Challenger tragedy and the postponement of Galileo, the NASA schedule is uncertain. Several foreign misisons are planned in the next few years (see chapter 6); however, the extent of U.S. participation will probably be minor, and support for the reflectance spectroscopy program is not a consideration. The only certainty at this time is that reflectance spectroscopy experiments will eventually fly on Galileo, Mars Observer, and other NASA missions.

Because funding is linked to missions, the slipping mission schedule poses an immediate and serious threat to the scope, balance, and quality of the overall research program. In addition, the mission budgets, especially for data handling and analysis, are decreasing. The Mars Observer VIMS budget for measurement planning and data processing, for example, is a factor of 3 to 5 too low, especially in light of the slip in the Galileo Project. In similar situations the basic resarch budget has been tapped to supplement the shortfall, further destabilizing the program.

As discussed above, the program is leveraged, and is at or below the critical mass necessary to meet the objectives of future missions in both direct support and in providing a science and technology base. Thus the main issue regarding the schedule of the program is how long the present effort can survive.

Personnel and Facilities

Personnel

The scope of the reflectance spectroscopy program is determined by resources for both personnel and facilities; however, the larger share of the cost is for personnel. The size and nature of the science community are outlined in chapter 5, tables 4-7. The community covers a broad science area in terms of discipline (geology, mineral physics, spectroscopy, astronomy, atmospheric science, etc.) and is highly varied in specialty (Mars, moon, asteroids, icy satellites, Io, etc.). Most scientists work across traditional discipline boundaries; while all have become knowledgeable in spectroscopy, few are spectroscopists by formal training. In general, the community is composed of planetary scientists who have become involved in the use and development of reflectance spectroscopy as a powerful new analytical tool.

Specialization has developed as the field has matured. There are a few (perhaps one to three) specialists in each area, such as asteroid mineralogy, icy satellites, reflectance theory, lunar rocks, mineral spectroscopy, the martian surface, etc. While there is a broad scope of understanding among the small group of investigators, specialization has progressed to the point at which personnel are not readily interchangeable. Programmatically, this means that if an investigator leaves (e.g., for lack of funding), it is likely that a key specialty will be lost. In certain areas the loss of even a single investigator would be a major setback to the program in terms of mission readiness.

It is more difficult, within the scope of this report, to judge the quality of the program. This is best done from a broader perspective in planetary science on the basis of the contributions of reflectance spectroscopy to our understanding of the solar system. It is known that the personnel in the program compete for resources through peer review of proposals by an interdisciplinary panel of planetary scientists, where published results are continually assessed. Unproductive researchers in this or any other area probably do not survive long in this environment, especially after several years of tight budgets. We believe that further reductions in numbers of investigators will result in reductions of high-quality science.

A deliberate effort has been made to bring a few new investigators into the program, even though the overall budget has offered little opportunity for growth and change. Shrinking programs are especially difficult for young investigators to enter: they have not had the opportunity to produce extensive research results, and they must compete with established scientists. While this problem is found in many other science areas, there is a unique and important difference in the case of the reflectance spectroscopy program. With the schedule for NASA planetary missions extending into the next century, and with the existing commitment to fly reflectance spectrocopy experiments on all or most of those missions, young scientists must be trained now and supported after they graduate to provide the necessary long-term continuity. Given the major technical challenges discussed above, we cannot skip a generation or two of graduate students and then call on future new graduates to meet the unfolding mission challenges.

Facilities

The facilities in use in the NASA solar system studies reflectance spectroscopy effort are listed in chapter 4, tables 4-7. As discussed above, these facilities were only partly purchased with funds from this NASA program and are only partly operated and maintained by yearly funding from the program. There is a wide range of adequacy in the various laboratories. There are one or two well-equipped and up to date U.S. laboratories capable of measuring the spectra of samples under controlled conditions, although none is capable of handling frozen volatiles adequately. Most facilities operate below potential because of outdated equipment and/or lack of funds for operating personnel and for maintenance and repair.

Laboratories equipped for studies of samples and telescopic measurements are generally also used by outside investigators. Some scientists in the program rely entirely on the facilities of others. This cooperative approach is desirable and conservative of resources; however, NASA has not consistently maintained or increased operations funding for the institutions that in effect serve as program facilities.

Computer facilities differ widely in nature and adequacy throughout the program. In general, the program has not been able to purchase computers for investigators, and other programs or institutions have borne these costs. To date, most of the research in the program has not been computation-intensive. This is now changing rapidly, as spectral analysis increasingly involves image cube processing. Few investigators have image cube processing facilities, which are costly and require additional personnel for operation and development. In the present budget climate it is desirable to concentrate limited resources for image cube processing in a few laboratories. In the long term, hardware costs may decrease enough to allow wide distribution of imaging cube processing facilities; however, the costs of personnel for operations, maintenance, and software development will probably not diminish.

Interface With Other Scientific Areas

Planetary Science

Because reflectance spectroscopy is a technique within the broader field of planetary science, it is essential that there be strong cross-disciplinary ties among investigators. The program has evolved naturally in this direction; however, cross-disciplinary work does not always fit conveniently within NASA organizational and programmatic structures. Funding is usually along disciplinary lines, and even conferences and workshops are often organized by discipline. For example, the planetary reflectance spectroscopy data set and the instrumentation and data reduction facilities are supported mainly through the Planetary Astronomy Program but the analysis and laboratory studies are funded mainly through the Planetary Geology and Geophysics Program. The Planetary Atmospheres program is also involved. It is essential at this point in planetary science that no discipline area be isolated.

Among the ways to facilitate communication between scientific areas are consortia, coordinated projects, and topical conferences and workshops. NASA can directly influence the amount of communication among scientists by its funding actions. For example, there has been discussion recently about the need to have remote sensing specialists and photogeologists work more closely. Although some collaboration already exists, interaction between these groups has been limited for the last 3 years. The small FORSE consortium comprised workers in the areas of photogeology, spectroscopy, planetary astronomy, radar, and theory, and included various specialists on individual planets. This group produced a series of multidisciplinary papers on planetary surfaces over a period of about 6 years. Such cooperative efforts are minimal in today's funding climate, owing to restricted funding of investigators' time and other resources, and to severe restrictions on travel. Thus, at the time in the evolution of the planetary program when we should be integrating the results of the past decade in a multidisciplinary way in preparation for the next generation of missions, we are instead slipping into increasing isolation.

The solution to this problem lies partly with the scientists and partly with NASA. We suggest that the scientists take the responsibility and the initiative to promote cooperative multidisciplinary efforts (an example is the successful MECA project). Modest funding along with programmatic encouragement will be required from NASA.

Terrestrial Program

A decade ago reflectance spectroscopy was a minor part of the scientific study of Earth and of the NASA terrestrial program. Landsat provided images in four broad bandpasses which had been chosen for agricultural purposes. Geologists exploited the broad coverage of Landsat from a photogeological point of view; however, mineral and rock identifications were not facilitated by the data available. Today NASA is involved in an active terrestrial geology program that is aimed at the use of imaging spectrometers on a space station in the 1990s. Imaging spectrometers are being developed and flown in aircraft. Scientists have found new ways to use reflectance spectroscopy in studying Earth. Geologists in industry use high resolution field spectrometers and aircraft-mounted spectroradiometers for mineral exploration.

The terrestrial program has brought new resources into the area of geological reflectance spectroscopy. This has benefited the science; however, it also has placed the terrestrial program in competition for the personnel resources in the planetary program. The competition for experienced personnel will intensify as activities related to the space station accelerate, for the time frame for the space station overlaps that for the Galileo and Mars Observer missions.

We also note that the increasing use of reflectance spectroscopy in terrestrial mineral exploration and other commercial and government activities has created an additional draw on the limited personnel resources of the planetary program. This is especially evident in the trend for graduate students trained in reflectance spectroscopy to take jobs in industry and government. A similar problem exists with respect to key technical personnel.

Education

Universities are an important part of NASA's research effort in reflectance spectroscopy. Support for a graduate student can cost as much as $20,000 per year; facilities, equipment, and supplies require additional funds. The current funding for the reflectance spectroscopy program is not adequate.

As funding for an investigator diminishes it is often necessary to seek other support for a graduate student. Students who are forced to change research topics are unlikely to return to the original field. Students avoid research areas in which the prospects for continuity of funding are uncertain. These uncertainties, coupled with the poor job prospects in the planetary sciences, pose a difficult challenge for principal investigators and NASA program managers who are looking ahead to meeting the challenges of future missions.

A steady flow of new scientists is necessary for several reasons:

> Graduate students are an important and cost effective work force for research.
>
> Students and young scientists are a major source of new ideas and technology.
>
> Many of the experienced scientists working today will no longer be active when the currently planned missions are flown.

We have also noted previously that students trained in reflectance spectroscopy may obtain positions in the NASA terrestrial program and in a variety of industries and government agencies. The few students being trained today are not working in the planetary sciences.

Consequences of Funding Actions

Although we have been told that the proportion of the Planetary Geology Program funding for reflectance spectroscopy was modestly increased, the funding per investigator per year appears to have diminished in the last 5 years. Furthermore, as mentioned above, for the reflectance spectroscopy investigations planned for new missions (e.g., MOM/VIMS), measure planning and data processing budgets are a factor of 3 to 5 too low to carry out the required work. This load is historically transferred to the basic research program, where it cannot be borne.

We have identified possible scenarios for future management of the field of reflectance spectroscopy. Although some are not desirable, they are presented here.

Scenario 1. Continue the current downward trend in support per investigator and continue to apportion the budget cuts among investigators. Research groups of high quality are being squeezed from the program. A few investigators are receiving grants of $20,000 to $30,000, which is not sufficient to support a typical individual stand-alone research project (normally requiring about $100,000 per year); therefore investigators depend on other funded projects. It is the continuation of this trend that is of primary concern, for the broad science coverage and balance of the program are at stake.

Scenario 2. A small increase in funding would stabilize the program, keep pace with inflation, and allow for a maintenance mode in which the program is intact but resources are not adequate to meet the critical mission challenges ahead.

Scenario 3. If a substantial increase in support were available, the program could be stabilized, and a new level of effort could begin on mission-related challenges. Even if such funding increase were to begin in FY 88, there would be a lag period of a few years for gathering personnel and equipment. As discussed above, some investigators have taken on other research commitments as funding has diminished in the planetary reflectance spectroscopy effort, and these commitments will not be dropped immediately. As long as a balanced core groups exists, the transition could be made efficiently. If the program shrinks so that the remaining investigators are those who operate on the lowest survival budgets (usually those who are not supporting laboratory facilities), the program will not respond quickly to increased funding.

Scenario 4. A scenario unattractive to some investigators is the elimination of some investigators to maintain level or increased funding for others. This is the approach of consolidating around a few centers of excellence where facilities as well as investigators exist. In this case, it is difficult to maintain a balance, but it preserves a core capability which can be built on when (if) funding increases.

Program Initiatives

The highest priority must be given to stabilizing the progam, avoiding further deterioration of the funding base, and building that base to meet the mission requirements of the near future.

As a first step in strengthening the reflectance spectroscopy program, immediate measures should be taken to improve communications between the NASA reflectance spectroscopy program management and the mission-oriented activities in NASA, especially Galileo and Mars Observer. It is not clear that the mission planners or even the investigation team leaders are aware of the ongoing research requirements in reflectance spectroscopy, or that the NASA management is fully appraised of the mission reflectance spectroscopy drivers.

A specific effort should be made to coordinate the reflectance spectroscopy efforts in technique development in the planetary program and in the terrestrial program.

It is essential that the investigators in the program work closely with management to provide information and support in the efforts to stabilize the reflectance spectroscopy program. It is also important that investigators communicate effectively as a group. An annual or biannual meeting of investigators and management to discuss research and programmatic problems would be useful.

Program management can promote efficient use of existing resources by encouraging and funding consortia and cooperative research projects among scientists within the reflectance spectroscopy program, and including outside investigators.