Recommended Laboratory Studies in Support of Planetary Science

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1.0 Introduction

Planetary science in the next decade will include major spacecraft missions to inner and outer solar system targets. Interpretation of these mission observations requires knowledge of fundamental physical and chemical properties of planetary materials. Much theoretical work at present depends upon rough estimates of basic parameters that could be measured under carefully controlled laboratory conditions. Due to the exotic nature of many planetary environments, these investigations are unique, challenging, and generally expensive for the individual researcher. Although planetary science has benefited from access to results from a wide range of industrial investigations, some of which happen to overlap or approach our own topics of interest, the state of the art has now reached a point where specific laboratory efforts are needed to push the science to the next level.

While funding for laboratory work has traditionally lagged behind mission operations funding, growing recognition of the many areas in which concerted laboratory efforts will yield exponential scientific returns has led a number of researchers and managers to call for increased funding of laboratory studies over the coming decade to support the next generation of spacecraft missions. It is critical that support be directed toward work that is immediately relevant to mission and science objectives. This review is intended to provide background and context to assist researchers and managers in evaluating the needs and priorities of the planetary science community.

The areas we found particularly dependent upon laboratory studies included atmospheric composition and chemistry, surface composition and chemistry, planetary geology and geophysics, planetary interiors, astrobiology, and astrophysics. Most of the necessary laboratory work for compositional studies involves spectroscopic characterization and creation of spectral libraries for planetary materials under appropriate conditions. *In situ* and analytic work is needed to understand planetary formation as revealed by interplanetary dust grains, meteorites and other extraterrestrial samples. Reaction rates and yields are needed for chemistry occurring in planetary atmospheres and surface materials. Sputtering yields and ultraviolet photochemistry are in particular need of study. Other types of experiments include characterization of physical parameters for use in theoretical modeling and interpretation of observations. Rheological properties in particular need quantification under planetary conditions appropriate to icy bodies in the outer solar system.

2.0 Atmospheric composition

Every planetary atmosphere has unique dynamics, weather, chemistry, and interactions with the space environment. Understanding these processes generally requires quantifications of the atmospheric composition obtained from remote sensing using microwave to ultraviolet spectral intervals. In fact, almost every physical phenomenon that influences the radiative transfer of a planetary body can be detected and quantified from the variation of specific spectral features, *provided there is sufficient reference spectroscopy available to interpret the observations properly*. At present, the fundamental spectral information required is *incomplete, inaccurate and unorganized*. A summary of the current state of the art is given in the white paper by Brown et al. (2009), along with recommendations and priorities for new laboratory research. This review emphasizes that deficiencies in laboratory results, not planetary observations, are the primary limiting factor that hinders (or even prevents) proper interpretation of planetary data. In the next decade, many shortfalls could be corrected using quantum mechanical modeling of laboratory measurements in order to predict spectral signals at the opacities, pressures and temperatures of planetary atmospheres and/or by obtaining direct spectral measurements as cross sections at planetary conditions. The cost of new laboratory studies would be only a fraction of what is spent on the missions: such an investment is both practical and powerful.

In general, planetary scientists do not have open access to all the required spectral knowledge because there is no well-organized and documented database tailored to planetary needs. Thus, a standardized system similar to the Planetary Data System (PDS) is long overdue. The necessary infrastructure for the laboratory work must be supplemented with a similar, virtual infrastructure for the maintenance of this information to ensure it is available to the community. Furthermore, Brown et al. (2009) recommend that sufficient support is needed to train the next generation of laboratory spectroscopists needed to create the spectral databases and maintain capabilities commensurate with the quality of future planetary observations.

3.0 Surface composition and chemistry

The situation for studies of planetary surface composition is very similar to that for atmospheric composition: much of our knowledge is derived from remote spectral studies, yet the availability of appropriate reference spectra lags far behind the available observations. Past, current and planned missions to Venus, Mars, and the Outer Planets carry ultraviolet (UV) and visible to near-infrared (VNIR) spectrometers yet few anticipated surface species have had their spectra acquired over this wavelength range using appropriate pressures, temperatures and viewing geometries. Published spectra of cryogenic ices are useful for identifying the general location of absorptions, but to model observed spectra and retrieve surface abundances, reflectance spectra or optical constants (real and imaginary index of refraction) are required. Furthermore, these need to be measured on samples of sufficient thickness that VNIR absorptions are clearly represented. Spacecraft instruments on many recent and planned missions (Galileo, Cassini, Mars Reconnaissance Orbiter, New Horizons, Europa – Jupiter System Mission, Titan-Saturn System Mission) measure VNIR reflectance spectra, and require reflectance spectra for comparison. Spectral databases for thermal spectrometers such as the Arizona State University Thermal Emission Spectral Library (Christensen et al., 2000) are also in demand. The current state of the art is summarized in a white paper by Ruff et al. (2009) along with recommendations for laboratory work that will enable interpretation of mission data and determination of surface compositions throughout the solar system. Spectral databases for Mars and the icy satellites, similar to the US Geological Survey Digital Spectral Library (Clark et al., 2007) are needed for interpretation of mission observations. A downloadable PDF chart (Dalton, 2008) depicting the wavelength coverage of published, peer-reviewed spectra of icy satellite surface compounds is available at http://mos.seti.org. Water, carbon dioxide, methane, and ammonia have had their spectra measured over the VNIR range of spacecraft instrumentation, in reflected light, at appropriate temperatures for the surface of the icy satellites. Reflectance spectra of several alkanes were recently published by Clark et al., (2009), including ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}) and extending up to decane ($C_{10}H_{22}$). Spectra for most candidate icy satellite surface materials either have not been published at all, or only over a subset of the spectral range measured by mission instruments, or at inappropriate temperatures, or have only been measured in transmission or absorption. Laboratory work must be conducted in the next decade to develop spectral databases for surface species of interest, measured under the conditions of planetary surfaces, using appropriate temperatures, ambient pressures, wavelengths, and viewing geometries. In addition to pure phases, spectra of molecules diluted within plausible host phases (H_2O, CO_2, N_2 etc.) are also needed for comparison, as such species interact to change the spectrum in ways that are difficult to predict on purely theoretical grounds: changes that have thus far received little attention and must be characterized empirically before theories can be developed to predict the spectra of such ice mixtures. Where possible, transmission measurements should be converted to optical constants, which can be used for nonlinear mixture modeling based on radiative transfer theory. Spectral databases for in situ techniques such as Raman spectroscopy are also needed, and will become more valuable with the prospect of future landed missions.

Understanding the chemistry of surface compounds and the processes that create them will shed insight on many scientific questions dealing with planetary formation and subsequent evolution. Reaction rates are needed for planetary conditions of extreme heat and extreme cold. Studies of aqueous geochemistry in planetary subsurfaces, soils, and interior oceans (on icy satellites) require laboratory measurements of reaction rates and production values. Radiolytic chemistry, driven by charged particle bombardment, requires specialized facilities for study. Photochemistry, particularly driven by ultraviolet light, is important at Mars, the icy satellites, Titan, and on outer solar system objects. Hodyss et al. (2009) describe the needs of surface chemistry studies for the next decade and provide recommendations for laboratory work that will help drive the field forward. Quantitative measurements of production and destruction rates are needed for molecules exposed to particle and photon radiation; also needed are reaction rates for species trapped in ices, and diffusion rates at temperatures relevant to icy satellites. Sputtering yields, fragmentation patterns and velocity distributions of sputtered molecules are poorly known at present and should be investigated.

4.0 Geology and Geophysics of Solid Planets

Laboratory measurements on the physical properties of planetary material analogs provide key support to the definition of science and measurement objectives, instrument design, mission planning, and data interpretation of ground-based and space exploration. These are summarized in a white paper by Castillo-Rogez et al., (2009), with recommendations for necessary studies that will raise the level of scientific understanding and the capabilities for interpreting mission observations. In some situations, models are a primary source of information on geophysical evolution and internal structure. These models rely on phase relationships and thermophysical properties for the materials inferred from observations or based on cosmochemical models. While these properties are relatively well understood for water ice and silicate materials, there is a general lack of such data for multiphase materials and materials characterized by a complex microstructure. The role of minor chemical constituents, and physical properties such as porosity, texture, and the present of partial melt have received little attention.

New types of materials,whose geophysical significance has been highlighted by observations obtained during the last decade, need to be studied in the laboratory. Examples include methanol hydrates, ammonia hydrates, clathrate hydrates, hydrated salts and sulfuric acid, methane and nitrogen ices, organics, permafrost, and very porous materials analogous to comets and ring particles. For all these materials there is a dire lack of thermal and mechanical property data, which is limiting the information that can be inferred from geophysical models of the relevant planetary bodies.

The last decade has also seen a number of emerging research topics and the need for laboratory simulations that can address specific geophysical processes: thermal and compositional differentiation, flow in planetary liquid layers, friction along faults, shock wave experiments, cryovolcanism, magnetic field generation, interaction of strain systems, grain growth, etc. Geologic processes such as impacts, cryovolcanism, erosion, and aqueous geochemistry will be better understood after relevant experimemnts have been conducted.

Impact studies are needed to understand basic aspects of planetary accretion and collisional evolution of small bodies. An improved understanding of the effects of shock on meteorites and returned samples is necessary to discern their record of planet forming processes. Necessary laboratory investigations include materials science studies that characterize equations of state and high strain rate deformation (shock wave experiments), small-scale impact cratering and catastrophic disruption experiments, and studies of kinetic processes (e.g., shock-driven chemistry, interface instabilities and mixing).

How are materials mixed during planet formation? The mechanics and chemistry of giant impact events is still poorly understood. Improvements would address, for example, the origin of the isotopic similarity between the Earth and the Moon, the assumption of efficient mixing in the application of geochronometers, and volatile retention and the composition of magma oceans and atmospheres.

Shock wave experiments have been revolutionized by the development of shock facilities using pulsed power techniques (e.g., lasers at Lawrence Livermore National Laboratory and the University of Rochester and the Z Facility at Sandia National Laboratory). The drive pulses may be shaped to attain a much wider range of pressure-temperature paths than available in mechanically-driven shocks. These facilities have also needed to develop much faster diagnostic equipment. However, because of the limited volume of material that may be studied with these techniques, mechanically-driven shocks are still necessary to investigate heterogeneous materials and any effect where longer length scales are important. In addition, the development of extremely high spatial and time resolution video recording systems enables new quantitative studies of impact phenomenology. The pulsed-power facilities have developed a strong user community among scientists studying the deep Earth, and should be utilized by planetary researchers as well.

Several of the missions envisioned for the next decade are considering shallow radar instruments on their payloads. Databases to support the planning of ground-penetrating radar observations, especially penetration depth prediction, rely on dielectric databases that do not yet exist for many materials, especially multiphase water-rich materials. In order to properly support the utilization of this relatively young technique and increase the science return of radar observations, there is a drastic need to acquire the relevant databases. A similar need has been identified for supporting electrical and seismic measurements conducted from landed packages.

5.0 Astrobiology

A key priority for astrobiology, and upcoming missions pertaining to astrobiology, is the development and determination of biosignatures and metrics for assessing habitability. Laboratory experiments are critical to this effort. Our understanding of the chemistry and habitability of planets is limited by the tools and techniques we use to investigate these worlds. Laboratory studies thus serve the dual utility of a) providing a conduit for instrument development, and b) providing the necessary tether from spacecraft data to scientific interpretation.

Astrobiology specifically needs advances in capabilities for remote, orbital techniques for assessing biosignatures and habitability. These techniques should be decoupled from photosynthesis, since on many of our astrobiology targets (e.g. Europa, Enceladus) photosynthesis likely represents a highly marginalized niche. Interestingly, much of the science of terrestrial biology is limited to studies in the environment or the lab; beyond photosynthesis little attention is currently given to remote sensing of biosignatures. Laboratory studies utilizing spectroscopic and spectrometric instruments can serve to close the gap between our understanding of life on Earth and our desire to investigate, detect and understand life on worlds beyond Earth.

6.0 Laboratory Astrophysics

Laboratory astrophysics is the branch of planetary/galactic/extragalactic astrophysics that focuses on conducting laboratory studies that enable a better understanding of the observed phenomena. Laboratory astrophysics is one of the four pillars of astrophysics: Observations, Modeling, Laboratory Studies, and Missions/Instrumentation. Laboratory astrophysics will derive collisional cross-sections to understand atmospheric processes, radiation processing of ice/mineral/salt surfaces through laboratory simulations, and high-pressure properties of subsurface analogs to understand the interior processes. American Astronomical Society (AAS) Working Group of Laboratory Astrophysics (WGLA, www.aas.org/labastro) has also submitted a white paper on "Laboratory Studies for Planetary Sciences" (Gudipati et al., 2009) detailing how various branches of laboratory studies address the needs of planetary sciences.

Most of planetary science needs can be divided into interior, surface, and atmospheric processes. We recommend increased funding for focused laboratory studies that have direct impact to improve our understanding of planetary behavior in these areas.

The following laboratory studies are prioritized by WGLA:

- Laboratory studies that are related to in situ missions
- Development of spectroscopic databases covering mm waves to X-rays.
- Derivation of optical constants of cryogenic ices, organics, minerals, salts, and a mixture thereof in the 0.1 – 500 microns region.
- Detection of isotopes with high sensitivity.
- Understanding reaction mechanisms in the interior, surface, and atmosphere.
- Formation of aerosols from molecular precursors in planetary atmospheres.
- Better understanding of surface catalysis reactions involving gas-phase species.
- Simulations of interior processes.
- Evolution of organics on Mars and outer solar system;

7.0 Conclusions and Recommendations

Over the last four decades, planetary science has advanced due to the availability of remote and in situ observations of atmospheres, surfaces and interiors. Mission instrumentation and theoretical understanding have continuously advanced. Laboratory studies, due largely to their expense, have been deferred but are now needed more than ever, and the stage is set for dramatic advances in several arenas if support for certain basic research can be maintained. This level of support is a fraction of the cost of missions, yet has the potential to significantly increase the scientific return to be gained from current and planned spacecraft missions.

We specifically recommend the development and maintenance of spectral reference libraries for atmospheric and surface composition studies, in ultraviolet, visible, infrared, and microwave spectral ranges. Materials must be measured at the appropriate temperatures, pressures, wavelength ranges and viewing geometries for applicability to spacecraft observations of planetary surfaces and atmospheres. Many gas, mineral, and volatile ice species have yet to be spectrally characterized under conditions appropriate to planetary environments.

Thermophysical properties and dielectric constants for many materials must be measured in order to optimize science return from current and planned missions. Phase diagrams are needed, extending into high pressure and low temperature regimes, for many planetary materials. Basic physical parameters, particularly rheological properties such as Young's modulus and viscosities, are needed for ice mixtures relevant to icy satellites. Simulations of geologic processes, including volcanism, cryovolcanism, and impacts are needed to validate models and improve interpretations of mission observations.

The above recommendations refer to the highest priority laboratory work that we have been able to identify. From a scientific perspective, grant support of studies that make headway into these topics will substantially improve capabilities required to interpret ground-based and mission observations of planetary atmospheres, surfaces, and interiors, providing the required foundations to push planetary understanding to the next level.

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