

Laboratory Studies in Support of Planetary Geophysics

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Executive Summary

Laboratory measurements of physical properties of planetary materials provide key support to the definition of science and measurement objectives of ground-based, orbital, and lander observations; instrument design and calibration; mission planning; and analysis and interpretation of retrieved data. In some situations, models are a primary source of information to address geophysical features that cannot be directly measured (e.g., subsurface liquid layers). Currently, there are an insufficient number of laboratories equipped to measure the physical properties of materials over the entire range of conditions relevant to planetary objects. The most extreme conditions and the most exotic materials have been little studied in laboratory due to challenging experimental constraints and the prohibitive cost of laboratory implementation and long-term maintenance. We recommend increased support from space programs to laboratory measurements of the thermophysical properties of planetary materials relevant to the space research priorities envisioned for the next decade.

1. Subdiscipline Overview

This white paper addresses laboratory experiments dedicated to supporting the geophysical investigation of planetary bodies. The topics and issues addressed in this document apply to all classes of objects: telluric bodies, giant planets, icy satellites, asteroids, comets, Kuiper-Belt Objects, exoplanets, etc. As such, it is relevant and complementary to other white papers dealing with these specific objects.

The role of experimental research in physical properties of materials in planetary exploration is multifold. In general, the interpretation of all geophysical techniques in terms of planetary body formation, evolution, and current state, relies on the knowledge of the physical properties of the materials expected or detected at the observed bodies. Physical properties of samples synthesized in the lab are necessary for comparison to observational measurements of planetary objects. Specific science investigations benefiting from a comprehensive laboratory research program on material properties are summarized in Table 1.

Some bodies have been subject to close-up geophysical exploration, and still, their general structure and geophysical evolution remain sources of questions. For some of these questions, laboratory work is a primary source of information, e.g., flows in liquid core and ocean materials. For many others, shape, mass, and surface spectral properties are the only constraints on internal structure. In both cases, geophysical models based on accurate and realistic input parameters may contribute to better understanding these objects. For example, some of the first models of the icy Galilean satellites by Consolmagno and Lewis (1978) relied on only a few observation-based constraints. Still these geophysical models highlighted the possible presence of a deep liquid water layer in this category of objects, a key driver for the subsequent orbital exploration.

The past decades have seen progress in several areas of planetary geophysics and new sets of questions arising from ground-based, orbital, and *in situ* observations. Our understanding of planetary bodies will keep improving during the next decade with about a dozen missions traveling all over the Solar system and twenty more at various stages of development, whose science definition will in part rely on geophysical modeling, and, thus, laboratory data. Ongoing research and future needs define the landscape of the experimental research to be carried out in the next decade, which we present in Section 2. Then we address the challenges inherent to this

discipline of experimental research (Section 3), and we suggest recommendations for the review panel to consider (Section 4).

Table 1. Contribution of geophysical observations, modeling, and laboratory measurements to science questions pertaining to better understanding the formation and evolution of planetary bodies.

<i>Science Questions</i>	<i>Space/Ground-based/Lander Observation</i>	<i>Modeling Approach</i>	<i>Parameters/Laboratory Measurement</i>
What is the composition and structure of subsurface material?	Electrical properties from lander	Subsurface evolution	Electrical properties in the ac/dc frequency regime
	Dielectric measurements from microwave and radio science bistatic experiments	Modeling of wave-ground interaction: identification of volatiles and structural elements	Parametric dielectric measurements
	Seismic velocities and attenuation from Seismometry	Inversion of velocity profile into density, temperature, and viscoelastic profiles	Acoustic wave velocities, Viscoelastic properties as a function of frequency
What is the global internal structure?	Gravity measurements, Shape, Rotation (includes librational response, polar wander), orbital properties	Thermal evolution, assessment of the extent of differentiation	Material properties under planetary T-P conditions: <u>Rheological</u> : e.g., viscosity, strain rate, fracturability. <u>Thermodynamic</u> : e.g., Phase relationships from petrologic, pressure-volume, calorimetric measurements, Equations of states <u>Thermophysical</u> : density, heat capacity, latent heat
	Sounding radar	Dielectric inversion. Identification of deep reflectors among clutter	Parametric dielectric
	Seismometry		Viscoelastic properties as a function of frequency
What is the interior thermal structure?	Surface temperature and heat flux (e.g., Far infra red or in situ measurements), geological mapping	Heat transfer (conductive)	Thermal properties (conductivity, specific heat)
		Convective heat transfer	Viscoelastic properties Diffusivity
What are the power sources and endogenic processes driving internal and geological evolution?	Surface temperature and heat flux	Tidal dissipation in models combining geophysical and dynamical evolution	Viscoelastic properties at orbital frequencies
	Orbital properties, secular acceleration		
	Geological mapping (volcanism, tectonics)	Cryovolcanic activity	Thermophysical properties of partially molten material

2. Science Rationale and Objectives

We summarize the rationale for advocating a healthy and sustained program of laboratory research in support of the geophysical exploration of planetary bodies. A more detailed description of the science rationale can be found in the abstracts of the *Science of Solar System*

Ices: A Cross-Disciplinary Workshop that was organized in Oxnard, CA, in May 2008¹. Presenters were asked by the workshop organizers (including the lead author of this document) to summarize the laboratory work that would be most suitable to enable strong progress in their respective fields. The present document is partly based on that input.

2.1 Discoveries over the Past Decade Reveal New Categories of Materials and Processes Requiring Investigation in the Laboratory

(a) *Increased constraint on the composition of some planetary objects* requires that the thermophysical properties of a number of materials be studied in the near future. These include, but are not restricted to: methanol hydrates, detected at the surface of KBOs (Barucci et al. 2006); ammonia hydrates detected on Charon and in Enceladus' plumes; nitrogen and methane ices, detected at the surface of TNOs, e.g., Triton; organics whose extensive presence in meteorites and outer Solar system (Titan and Enceladus) may have geophysical consequences; hydrated salts and sulfuric acid suggested for the composition of Europa's shell; clathrate hydrates whose presence throughout the Solar system has been strongly supported by recent observations at, e.g., Mars sediments (McMenamin and McGill 2009) and Enceladus (Kieffer et al. 2006); hydrated silicates expected in the cores of water-rich bodies (Scott et al. 2002).

(b) *Identification of new categories of objects*: The last decade has seen an increased number of observations of outer Solar system objects: transneptunian objects, cubewanos, dwarf planets. These observations require investigation at the very low temperatures characteristic of these objects. Increased modeling of these objects supported by the appropriate thermophysical data will help assess their habitability potential and will help define the science rationale for continued exploration of these bodies. Close-up observations by the *Cassini-Huygens* mission of Saturn's rings, discovery by that same mission of a multitude of moonlets in the Saturnian system, discovery of activated asteroids (main belt comets) and impact of comet Tempel 1 leading new constraints on cometary material provide a rationale for supporting increased research on very porous material. Recent detection of water ice in the Martian subsurface and hints that water ice would also be present in the Moon entails more research on permafrost samples.

(c) *Increased evidence for the presence of liquid layers in many planetary bodies*: i.e., Europa and Ganymede, the Moon (Williams et al. 2001), Enceladus (Porco et al. 2006), Titan (Lorenz et al. 2008), Mercury (Margot et al. 2007). Liquid layers may be involved in the production of internal magnetic field in these objects. In telluric bodies there is a need to better understand the mechanisms of magnetorotational instability in a viscoelastic fluid. Also understanding the generation of magnetic field in a metallic core relies on detailed knowledge of the iron and iron-rich systems and to properly assess the chemical consequences of metallic core crystallization. In large water-rich bodies, the presence of a liquid ocean is an important factor for habitability. It has recently been suggested that subsurface ocean dynamics driven by mechanical forcing is a potentially significant source of heat (Tyler 2008). Quantification of flows and associated energy require intense numerical modeling and can be best supported by laboratory simulations (Noir et al. 2009). In icy bodies the composition of these layers is likely to be complex (e.g., Zolotov 2007). The properties (stability, thermodynamics and physical properties) of hydrated species in aqueous phase expected in the high-pressure conditions of putative icy satellite oceans remain to be studied in a systematic manner in dedicated facilities.

¹ <http://www.lpi.usra.edu/meetings/scssi2008/>

(d) *Boundaries and Transition Layers are Major Components of Planetary Dynamics.* Upper boundary layer and phase, chemical, and thermal boundaries are key components of planetary bodies. They may be regions of chemical transfer, increased energy dissipation and concentrated strains. They may also drive thermal evolution. Simulations coupling different processes expected at major interfaces would increase the realism of geophysical models, e.g., heat and volatile transfer through regolith (Travis et al. 2009); chemical and geophysical modeling of hydrothermal activity across the interface between a rocky core and ocean (Palguta et al. 2008).

2.2 Laboratory Work Increases the Science Return of Ground-Based Observations and Space Missions

There is need for continuous improvement in models of planetary bodies as our understanding of their composition increases. Studies of planetary dynamics and evolution open new windows of pressure, temperature and composition for the study of material properties.

(a) *Develop or improve knowledge of phase relationships of planetary materials over a wide range of pressure and temperature.* This is especially the case for the very high pressures phases of materials relevant to the conditions expected in giant planets. Laser-driven shocks have driven several materials to the pressures and temperatures necessary to reach ionic or metallic states (e.g., D₂, H₂O, SiO₂, C). Future quasi-isentropic experiments will be able to probe directly the range of P-T states found in the interiors of giant planets. and of complex mixtures relevant to outer Solar system bodies (see 2.1). There is also the need to fill in the holes in the databases of physical properties of some planetary materials. This is especially the case for amorphous ice, cubic ice, high-pressure phases, slurries, multiphase materials, as well as the volatile compositions listed in 2.1(a). Additionally, knowledge of the effects on phase stability and phase change of minor constituents is badly lacking.

(b) *Assess the role of microstructure and minor chemical constituents on the physical properties of materials.* Complex microstructures defined by texture, i.e., the shape and size of grains; lattice-preferred orientation (LPO), the distribution of crystallographic orientations of grains in a solid; the distribution of melts and minor constituent phases, especially as related to grain boundaries; porosity distribution; textural relationships between major constituent phases; intrinsic and extrinsic diffusion; etc.; can all have profound effects on the fracture, flow, and transport properties of planetary materials. Second-phase impurities may decrease the melting temperature of multiphase materials leading to low-temperature differentiation. Learning the fundamental physics behind rheology, heat transport, and other dynamic processes key to understanding planetary evolution and behavior requires detailed understanding of the microstructures of planetary materials, and how these microstructures evolve (e.g., grain growth, melt segregation, shear localization) with time and with strain.

(c) *Geophysical processes for which laboratory simulations are key.* Specific needs include the thermal and composition differentiation (e.g., metallic core; low-temperature differentiation in icy bodies) in low-gravity conditions, flow in planetary oceans (see 2.1.c), friction along faults (e.g., Enceladus' tiger stripes), shock wave experiments to constrain the equations of state of high-pressure materials, cryovolcanism, plumes and jets, magnetic field production, interaction of strain systems in materials simultaneously subjects to different stress regimes, material response to cyclic stress simulating tidal stress, grain growth, liquid-like behavior of grain surfaces at sub-solidus conditions, etc.

2.3 Support the Preparation of the Next Decade of Space Exploration

A number of future missions already en route or in phases D and E are planned for the next decade: *Messenger* and *Bepi-Colombo* at Mercury, the *Grail* mission at the Moon, *Mars Surface Laboratory*, *Dawn* Mission at Vesta and Ceres, *Juno* at Jupiter, *Cassini Equinox Mission*, *New Frontiers* at Pluto and Charon, *Rosetta* and *EPOXI* missions to comets.

A number of missions targeting a large variety of objects are also in plans. Their science definition during the proposal phase, instrument design during the early phases of preparation, the definition of the tour during the mission planning may rely in part on understanding the properties of the materials expected in the targeted objects. Among the missions currently considered for consideration in the Decadal Survey: *Venus Geophysical/Geological Orbiter*, ARTEMIS Mission and Geophysical Network on the Moon, *Europa and Jupiter System Mission*, *Titan and Saturn System Mission*, ARGO Mission to Triton, the Neptune System, and a KBO, Ceres lander, missions to large asteroids, Trojan Reconnaissance, Robotic mission to Phobos and Deimos, Uranus Orbiter, Saturn probe, Jupiter probe, and more...

Physical properties of planetary materials in the lab are necessary for comparison to observed physical measurements. We highlight below two major types of instruments whose application to planetary exploration is expanding, which requires the development of appropriate databases.

(a) *Radar instruments*, e.g., the CONSERT experiment on Rosetta, or the suggested dual band radar sounder for the *Europa and Jupiter System Mission* payload strawman. The databases of dielectric properties needed to support these experiments must be enhanced with more relevant mixtures of complex ices. The accurate knowledge of the dielectric properties of these planetary environments and their impact of the wave propagation matrix is crucial for the current data analysis from orbital sounder as MARSIS and SHARAD as well to optimize future observations (Heggy et al. 2001). The frequency and bandwidth of low frequency sounding radars is mainly optimized by the accurate description of the subsurface geoelectrical properties. Hence an unambiguous estimation of the penetration depth and the vertical resolution is constrained by the range of expected dielectric properties of the materials of the planetary upper crust.

(b) *Several of these missions also plan to include landing packages with electrical, thermal, and seismometry measurement capability*. The definition and planning of the science to be performed with these packages will benefit from the utilization of test-beds as has been extensively used for preparing landing missions to Mars (e.g., Peters et al. 2008). Electrical measurements are crucial when it comes to understanding the three-dimensional distribution of volatiles in a soil matrix (Chin et al. 2007). Comparison between the inferred dielectric values deduced from radar sounding and imaging data to those measurements in the lab, will yield a more quantitative assessment of water-ice presence and its dust-salts contamination levels on several planetary subsurface.

3. Key Challenges of the Discipline

Thermophysical measurement of planetary materials requires the capability to make controlled samples, to characterize and certify their composition and microstructure, to test them and verify the reproducibility of these measurements, and then to interpret the result in a larger context.

(a) *The experimental measurements and simulations identified in this document imply the realization of laboratory setups able to handle a variety of extreme conditions:* fluid pressures as high as 1 GPa and solid pressures exceeding those obtainable in existing apparatus (300 GPa²), temperatures as low as 20 K or as high as 2000 K; vacuum conditions; low-gravity; low strain rates; high-velocity shock waves. The extrapolation of measurements obtained in “milder” conditions have proved to poorly predict the actual situations. Such facilities are generally unique and are therefore required to be custom-made, which involves significant technological development.

(b) *The production of complex sample compositions and structures is challenging.* This also requires the development of specific setups and in the case of low-temperature materials, the access to a cold room. Many compositions of interest are hazardous: flammable (hydrocarbons), corrosive (e.g., ammonia), etc. As a result, research on such materials has been inhibited despite its potential geophysical importance. The development of the capability to make quality samples requires a significant investment in time and funding.

(c) *Characterization of the sample composition and microstructure, of key importance,* depends on the availability of dedicated facilities: X-ray diffraction, cryogenic scanning electron microscopy (SEM), polarized (cryo-)microscopy, Raman spectroscopy, calorimetry, etc. Such facilities are scarce. For example, there is only one cryo-SEM in the U.S. equipped to perform Electron Back-Scatter Diffraction (EBSD), an elegant way of determining LPO. Utilization of such facilities requires specific training, and often technical support staff to help outside users.

(d) *Laboratory research is expensive.* The cost of laboratory research is well above the mean for theoretical and numerical research. After an initial phase of intense development, routine activity may involve time-consuming sample preparation and post-test analysis, technical support, expenditure of consumables, access to characterization facilities, equipment maintenance, upgrading, and periodic replacement of aging equipment. A laboratory-based project may also involve theoretical simulation of the tested processes, which can be computer-intensive (i.e., modeling of flow in liquid core). In general NASA R&A programs require laboratory-based research to apply thermophysical measurements to geophysical models, as it is not the goal of these programs to fund the development of databases. As a result, the average ROSES research grant must be split between laboratory support, laboratory investigation, travel to microanalysis facilities, geophysical application, and publication of results, so that the time actually devoted to data acquisition is limited.

(e) *Laboratory research takes time.* Sample production is a long process. Verification and validation implies multiple reproducibility tests. It takes many measurements before it becomes realistic to derive empirical relationships. Technical failures may stall a project for weeks or months. Training student and other personnel is time-consuming. As a result, a new project may not lead to breakthrough results before at least one year after its initiation, which is a potential concern for upholding financial support.

4. Recommendations

Based on the above considerations, we recommend that the Decadal Survey review panel advocate for the following points:

² <https://www.llnl.gov/str/December04/Weir.html>

- (a) Acknowledgement of the role of experimental research as a key component of planetary exploration and advocacy of a healthy laboratory research program meeting the needs of planetary exploration envisioned for the next decade.
- (b) Increasing funding levels for laboratory-based proposals to reflect the higher cost of these activities and to avoid the appearance of their being less cost-effective than typical theoretical studies reviewed by the same panels.
- (c) Provision of funding inside mission projects to support laboratory work dedicated to support specific instrument development and science planning needs.
- (d) Development of shared user facilities to provide capabilities generally out of reach for the single investigator, such as specialized environments (e.g., cryogenic, high-pressure), centralized microanalysis instrumentation, large-scale simulations, etc., managed, e.g., through NASA or NSF. For a sustained and productive program to be achieved, these facilities would have to have dedicated technical support.
- (e) Improved coordination between laboratories working on planetary materials; promotion of exchange of expertise and personnel; optimized utilization of existing facilities.
- (f) Establishment of a database for sharing government-funded laboratory results (data and background information), patterned, e.g., after the Planetary Data System database.
- (g) Allowance for ongoing upgrading and maintenance of facilities.
- (h) Training of an increased number of young researchers in laboratory techniques; increased visibility of laboratory work in education and other outreach activities.
- (i) Appropriate representation from the laboratory research community on the executive committees of professional societies and assessment groups.

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