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A Solar System Perspective on Laboratory Astrophysics

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1. Introduction

Planetary science deals with a wide variety of natural materials in a wide variety of environments. These materials include metals, minerals, ices, gases, plasmas, and organic chemicals. In addition, the newly defined discipline of astrobiology introduces biological materials to planetary science. The environments range from the interiors of planets with megapascal pressures to planetary magnetospheres, encompassing planetary mantles, surfaces, atmospheres, and ionospheres. The interplanetary environment includes magnetic and electrical fields, plasma, and dust. In order to understand planetary processes over these vast ranges, the properties of materials must be known, and most of the necessary information comes from the laboratory.

Observations of the bodies and materials in the Solar System are accomplished over the full range of the electromagnetic spectrum by remote sensing from Earth or spacecraft. Comets exemplify this; molecular and atomic identifications are made from the hard ultraviolet to radio wavelengths, while X-rays are emitted as comets interact with the solar wind. Gamma rays from the surfaces of the Moon and asteroids are diagnostic of the mineral and ice content of those bodies; eventually, gamma rays will also be observed by probes to comets.

A number of planetary materials are available in the laboratory for extensive Study: rocks from the Moon, Mars, several asteroids, as well as dust from comets (and perhaps the Kuiper Belt) are closely studied at every level, including atomic (isotopic). Even pre-solar interstellar grains isolated from meteorites are scrutinized for composition and crystalline structure.

Beyond the materials themselves, various agents and processes have altered them over the 4.6-Gy age of the Solar System. Solar radiation, solar wind particles, trapped magnetospheric particles, cosmic rays, and micrometeoroid impacts have produced chemical, physical, and morphological changes in the atmospheres and on the surfaces of all planetary bodies. These processes are not well understood, so studies in a laboratory setting are especially needed.

2. Laboratory Data Needed for Planetary Science

A number of problems in contemporary planetary science have generated specific needs for additional laboratory work, and we review a sampling of those here.

Planetary interiors: For the giant planets, the equations of state for H_2, H_2+He, and H_3 at pressures >3 MPa must be better understood. [1] How do the equations of state change

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[1] The equations of state describe the relationships of the directly observable quantities that specify the thermodynamic state of a system. For fluids, these are pressure, volume, and temperature (P, V, T); for solids these are the same quantities plus stress and strain components; for ferromagnets these are the same quantities plus the applied field H and magnetization M.

when H_2 is shocked? In the context of the interiors of the Galilean satellites it is important to study saline solutions, while other materials (notably ices) present in the interiors of large planetary satellites and distant bodies in the outermost Solar System (Kuiper Belt objects) require further investigation.

Planetary atmospheres: Various planetary missions already completed or in progress are driving the need for additional laboratory work. In studies of Mars, high accuracy measurements of line strengths of CO_2 and H_2O in the near-infrared are needed. For Jupiter and Saturn, spectral measurements of CO broadening by H_2 and He are relevant. Improved line strengths for PH_3 are needed in the far-infrared (100-500 μm).

In the Cassini investigation of Titan with the CIRS instrument, improved line strengths and line- broadening parameters are needed for several materials, such as nitriles and hydrocarbons throughout the mid- and far-infrared. The nitriles include HCN, HC_3N, and C_2N_2, acetonitrile (CH_3CN), acrylonitrile (CH_2CHCN) and proprionitrile (CH_3CH_2CN) in the 14-50-μm range. Among the hydrocarbons, pure rotation lines of CH_4 near 100 μm will probe the temperature of the lower stratosphere of Titan. Improved line strengths in the 12-30-μm range are needed for methyl acetylene (CH_3CCH) and allene (CH_2CCH_2) are needed. A possible condensate and component of Titan's aerosol smog is diacetylene (C_4H_2) requires further laboratory spectroscopic studies to support the data expected from the CIRS investigation.

There are unsettled questions regarding the colors of the clouds of the outer planets, including the source of the color in Jupiter's Great Red Spot. There may be a "weathering" phenomenon in the clouds, the consequence of which causes the NH_3 clouds of Jupiter and Saturn to lose their NH_3 spectral signatures over time. The coloring agents in the stratospheric clouds of Uranus and Neptune are also not understood.

Planetary surfaces: Surface materials include ices, minerals, and organic solids. There is a large body of reflectance and emittance spectroscopy of minerals, a lesser amount for ices, and very little for organic solids. All areas of laboratory investigation need support, particularly for ices and organic solids. Spectra alone are insufficient for modeling needs, because spectrum matching is an inadequate means for making identifications of materials present on a planetary surface, and is not sufficiently quantitative. Spectrum modeling by scattering theory (e.g., Hapke or Shkuratov) provides a more quantitative evaluation of species present, plus information on particle sizes, and critical details on the mixing of components. Spectrum modeling with scattering theory requires that the complex refractive indices of candidate materials be determined at a suitable spectral resolution and over the necessary range of wavelength. Such data are available for a very limited number of materials, thus restricting the range of modeling parameters that can be explored.

Specifically, there is a need for complex refractive indices from the UV to the mid-IR for minerals, ices, and organic solids of planetary interest. Minerals include igneous silicates, salts, carbonates, sulfides, and oxides. Ices include hydrocarbons and nitriles in amorphous and crystalline phases, and in matricies (N_2, Ar, H_2O). Organic solids include extracts from carbonaceous meteorites, terrestrial kerogens, and synthetic organics (tholins) produced by energy deposition in gases and solids of planetary significance.

Space processing: Planetary materials exposed to the space environment are impacted by solar UV, solar wind particles, galactic cosmic rays, micrometeoroids, and macrometeoritic collisions, all of which serve to alter the chemical, crystal, and microphysical characteristics of surface materials. These processes must be factored into the interpretation of remote sensing observations of planetary bodies, insofar as their effects are understood. There is a wide range of experimental studies that can be conducted in the laboratory to expand our understanding of the processes of sputtering, radiation darkening, organic production, ablation, and others.

3. Facilities

In addition to specific areas of laboratory measurements that are critical for the interpretation of planetary data, this subject has the unique and specialized needs for the study and preservation on Earth of materials from space. Meteorites and interplanetary dust particles collected on the surface, in the ice sheets, and in the high atmosphere, are a priceless treasure of extraterrestrial materials that arrive on our planet free of charge. To extract their secrets, these materials must be studied with the most modern analytical techniques, and they must be preserved for future studies. Additionally, extraterrestrial materials brought to Earth by space expeditions (including Apollo), also require study and preservation. This part of the equation is not free of charge.

Lab Facilities for Returned Samples: Preparations must be made for analysis of the samples returned from the Stardust, Genesis, Muses-C missions, and eventual returns from Mars and a comet nucleus. This can be accomplished through the establishment of a realistic laboratory instrument development program. The development of new analytical technologies is especially urgent, with the greatest need being for development of organic chemistry microanalysis. As new techniques are established and new analytical equipment becomes available, the program priorities should shift to outfitting and upgrading U.S. labs.

Lab Facilities for the Study of Planetary Materials: Several ambitious NASA planetary missions to planets, comets, and asteroids are in progress or in various stages of advanced planning. Critical to the correct and complete interpretation of the observational data acquired at great expense are laboratory studies that will provide data of the kind mentioned earlier in this report. Such work is often inadequately supported, either in existing laboratory facilities, or through the creation of new laboratories.

Curation: In preparation for the samples to be returned from the Stardust, Genesis, Muses-C, as well as anticipated returns from Mars and a comet nucleus, support for sample curation and handling is urgently needed at a significantly increased level over that which exists today. The proper preservation (and quarantine) of each returned sample for future investigations is of singular importance. The samples returned from each object will impose specific handling and storage demands, which must be addressed by separate, specialized facilities. The funding for these facilities, including long-term operating costs is very unlikely to be included in each mission's budget. In preparation for the return of cold samples from comets, development is needed in the areas of cryocuration, robotic sample handling, and biological quarantine.

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