

Space Weathering Impact on Solar System Surfaces and Mission Science*

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*Full references & other docs at http://nssdcftp.gsfc.nasa.gov/miscellaneous/space_weathering
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Abstract

Space weathering is the collection of physical processes acting to erode and chemically modify planetary surfaces directly exposed to space environments of planetary magnetospheres, the heliosphere, and the local interstellar environment of the solar system. Space weathering affects the physical and optical properties of the surfaces of planetary bodies, so understanding its specifics is critical for interpreting surface data from remote and landed measurements. For full coverage of space environmental measurements, we recommend expanded interdisciplinary cooperation between NASA's Planetary Science and Heliophysics divisions. To grow the field in the next decade and maximize impact on mission studies, we suggest a balanced mixture of laboratory measurements, modeling, and theoretical investigations in support of all missions.

Space Environments

Vast expanse of the space weathering environment interacting with solar system bodies is illustrated in Figure 1 by logarithmic horizontal scale of radial distance from the Sun to α -Centauri. Principal sources of energy for space weathering of planetary surfaces are UV photons, solar wind plasma, and energetic particles from the Sun, within a few hundred AU, and external sources of plasma and energetic particles entering into the solar system from the local interstellar environment. Beyond the realm of terrestrial planets and the asteroid belts, the solar influence significantly wanes with the decline in density of the expanding solar wind plasma and magnitude of the frozen-in magnetic field, while the interstellar influence progressively grows through interaction of interstellar neutral winds with solar ultraviolet radiation and the solar wind plasma. Across the heliospheric boundary region near 100 AU, now being explored by the two Voyager spacecraft, occurs a transition from supersonic (400 – 800 km/s) plasma flows of solar coronal expansion, the solar wind, to 26 km/s inward flow of the interstellar wind. This plasma contains both a bulk flow and thermal components associated with typical ion energies up to a few keV, and energetic components extending to far higher energies, ultimately to the full range

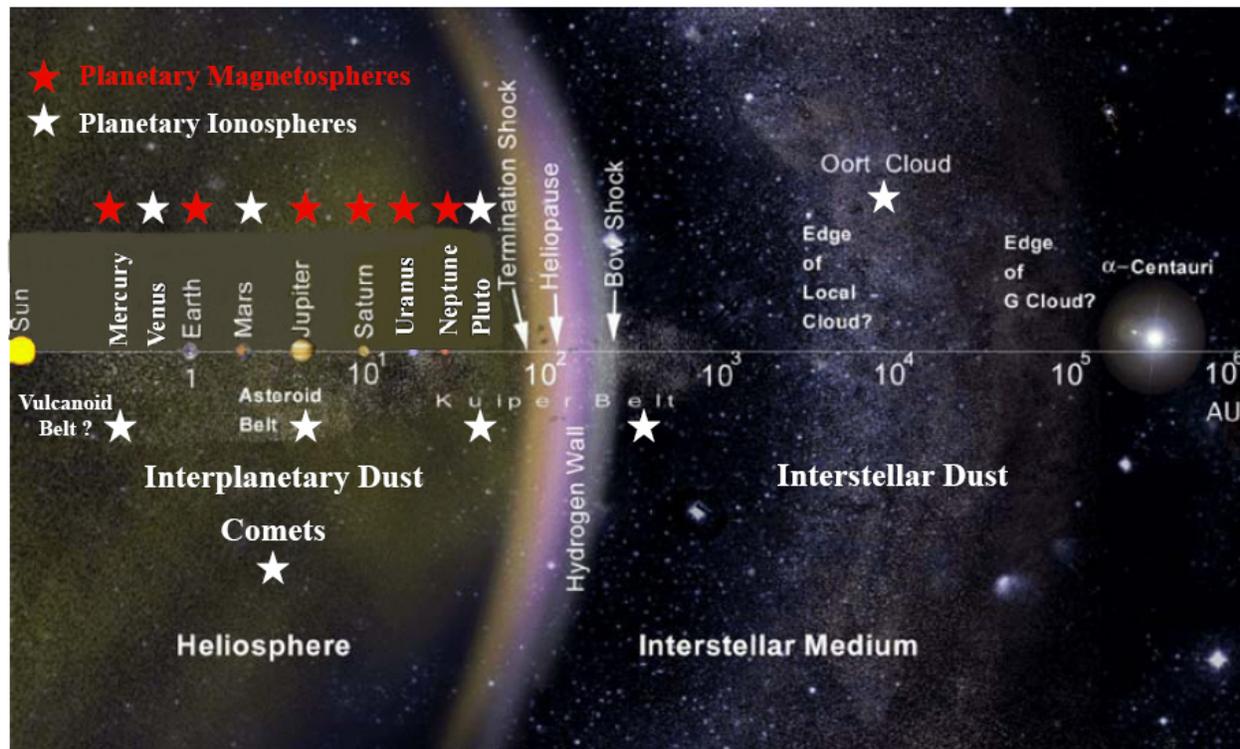


Figure 1. Logarithmic distribution of space weathering environments from the Sun to the nearest star.

of galactic cosmic ray ions easily penetrating into the heliosphere at GeV energies and higher.

The Sun contributes the innermost source of energetic particles in association with solar flare and coronal mass ejection (CME) events, the interstellar environment contributes the outermost sources, and the dynamics of the expanding and variable solar wind provide additional energy to MeV energies within the heliosphere. The solar wind termination shock, the supersonic-subsonic flow boundary crossed by both Voyagers (Stone et al., 2005, 2008), and/or the heliosheath region beyond this shock out to the heliopause, the contact boundary with interstellar plasma, *may* further accelerate plasma particles into the energetic range but this is not yet established by the Voyager measurements. Neither spacecraft detected local particle acceleration at the respective crossings, although the bulk of acceleration may be occurring elsewhere along the shock boundary (McComas and Schwadron, 2006). Other possibilities are that the heliosheath ions are energized by turbulent or reconnecting magnetic fields in the heliosheath, or that these ions originate instead from penetrating interstellar ions (Cooper et al., 2006; Cooper, 2008). As solar activity increases and then again declines within the next decade from the current minimum, the continuing Voyager measurements, supplemented by direct energetic neutral atom measurements of boundary region emissions by the Interstellar Boundary Explorer (IBEX) in earth orbit, are expected to resolve origin of the heliosheath ions and to locate the heliopause. What is already clear is that the termination shock boundary marks the transition from dominance of some space weathering effects, e.g. erosive sputtering, by the supersonic plasma flow to a broader range of effects from plasma and energetic particles at higher energies to the cosmic ray regime.

Within these expanding near-solar to heliospheric to local interstellar space environments we find the objects of primary interest to planetary science: the terrestrial planets, the asteroid belt, the gas and ice giant planets, comets, the Kuiper Belt, and finally the Oort Cloud. Aside from the first known member of the Kuiper Belt, Pluto, now officially designated as an ice dwarf planet, our direct knowledge of Kuiper Belt Objects (KBO) began with the first discovery in 1992, then followed to date by about a thousand other discoveries of such objects, including a few classified as members of the inner Oort Cloud. Presumably there are thousands more of similarly detectable size waiting to be discovered, and far more at smaller sizes. Looking back towards the Sun, there are also thousands of known asteroidal bodies, including Near Earth Objects potentially of concern for future Earth impacts, and as a remote possibility the first members of the fabled Vulcanoid Belt that might be found via increasing sensitivity of near-solar observations. At the smallest scales there are interplanetary dust grains, the source of the zodiacal light, extending down in size to nanometers or less (e.g., molecular clusters) and thought to arise from impact surface weathering of small bodies and from comet outgassing.

The red and white stars of Figure 1 denote the distinctly different space environments of solar system bodies with and without internally generated magnetic fields. Except for the highest energy cosmic rays and their atmospheric interaction products, the direct effects of space weathering do not extend to the solid surfaces of Venus, Earth, and Mars. While the planetary magnetospheres (red stars) substantially deflect interplanetary plasmas and energetic particles away from the atmospheres and underlying surfaces, even an ionospheric (white star) interaction arising from ionization of a thin atmosphere, or surface-bound exosphere, can significantly impede or totally inhibit access of space plasma to otherwise exposed surfaces. The surface of Mars is notably oxidized by solar ultraviolet irradiation and to a lesser extent from high energy (> 100 MeV) cosmic rays and solar energetic particles, while medium-energy (> 1 MeV) energetic ions can easily penetrate Pluto's microbar-pressure atmosphere to the surface. On the other hand, the acceleration of charged particles within the planetary magnetospheres, and

magnetic pickup of exospheric ions, provides additional and potentially more dominant energy sources for space weathering of surfaces exposed to those environments.

Space Weathering Effects

In remotely viewing and more closely encountering planetary objects of the solar system and beyond, we are often looking “through a glass, darkly” at objects with tenuous atmospheres and direct surface exposure to the local space environment. In each case this space weathering exposure acts via universal plasma-surface interaction processes (Johnson, 1990) to produce a thin patina of outer material covering and sometimes obscuring the endogenic materials of greatest interest for understanding origins and interior evolution of the affected object. Examples of weathered layers obscuring pristine ones are the radiation crusts (Johnson et al., 1987) on cometary nuclei, also on

Kuiper Belt and Oort Cloud Objects (Hudson et al., 2008), and the iogenic components of sulfate hydrate deposits on the trailing hemisphere of Europa. In the latter example, near-infrared spectroscopy is used for mapping of the surface distributions (McCord et al., 1998a,b, 1999, 2001; Carlson et al., 1999, 2005; Dalton et al., 2005; Hibbits et al., 2000), as shown for the icy Galilean moons including Europa in Figure 2. Formation processes of red-orange concentrations of non-H₂O materials are not well understood for any of these moons but appear to correlate to expected magnetospheric irradiation (e.g., Paranicas et al., 2001, 2009) on the trailing hemispheres for Europa and Callisto, and to latitudinal variations expected from deflection of magnetospheric plasma by Ganymede’s intrinsic dipolar magnetic field (Cooper et al., 2001; Khurana et al., 2007). Visible and UV spectroscopy are also used to map weathering products, e.g. O₂, SO₂, O₃, H₂O₂. Irradiation can make oxidants for life (Chyba 2000) but also obscure and even destroy chemical signatures of prebiotic and potentially biological evolution that would otherwise be high priority targets on potentially habitable worlds such as Europa and Enceladus. *For all these moons, and for others with global variations in relative contributions of different materials, the central one of space weathering remains as to how much of the spectroscopically mapped material is of magnetospheric or meteoritic versus intrinsic origin.*

Weathering processes include plasma ion implantation into surfaces, surface sputtering by plasma and energetic ions, photolytic chemistry driven by solar ultraviolet irradiation, and radiolytic chemistry evolving from products of charged particle irradiation. Simultaneous action of multiple processes can substantially change the outcome, e.g. ion sputtering of an impact regolith followed by photon-induced desorption of neutral species such as sodium (Yakshinskiy and Madey, 1999). These microscale interactions are not independent of macroscale structures since regolith structure from impacts, and underlying deeper structures from internal evolution, can affect the efficacy of certain plasma-surface interactions, e.g. sputtering as affected by porosity, and surface irradiation dosage as partly attenuated by local topographic shielding (Cooper and Sturmer, 2006). Topographic maps of disrupted icy surfaces on Europa, Enceladus, and other moons (e.g., Schenk, 2009; Schenk and McKinnon, 2009) make it clear that relatively

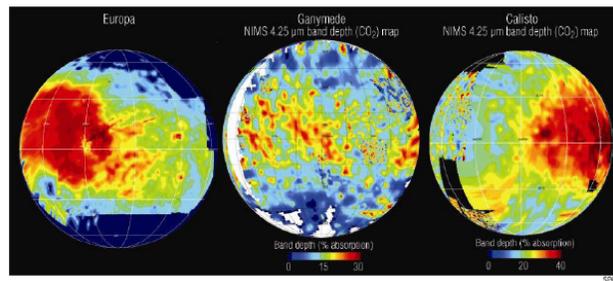


Figure 2. Near-infrared maps from the Galileo mission of non-H₂O surface materials on Europa (left, sulfate hydrates), Ganymede (middle, CO₂), and Callisto (right, CO₂). Red regions for Europa and Callisto are centered on the trailing hemispheres, consistent with expected magnetospheric effects.

flat laboratory surfaces cannot really simulate planetary icy surfaces. Chemical products of space weathering could also potentially impact subsurface evolution, e.g. mixed gas clathrate accumulation affecting thermal conductivity within Europa's ice crust (Hand et al., 2006) and gas-driven cryovolcanism from radiolytic chemistry on Enceladus (Cooper et al., 2009).

High porosity of nearly all space-weathered surfaces means that any incident ion, electron, photon or micrometeoroid is likely to enter this porous covering, or regolith, before hitting a surface so that various processes may happen in partially-closed spaces. Grains within the porous material provide enormously greater surface area for chemical reactions than at smooth outer surfaces typically used in laboratory experiments and models as planetary analogues. A prime example of regolith effect on space weathering is V-NIR reddening of surfaces in the inner solar system. Hapke (e.g., 2001) discovered that this was due to the thin patina of reduced material (Fe and Fe/Si compounds, poor in O) on lunar regolith grains. This patina could be produced by a combination of ion and micrometeoroid ablation inside of a regolith: Fe and Si ejecta stick to neighboring grains while O-containing compounds desorb and leave the regolith. In icy surface environments like Europa, porosity may play an important role in chemical activity of the irradiation surface for production of the surface-bound exosphere, mostly O₂ due to low efficiency of sticking to the surface (Shematovich et al., 2005; Cassidy et al., 2007), but with minor species produced in the ice and exosphere from sputtering and radiolytic chemistry driven by surface irradiation. Teolis et al. (2006) suggested that regolith porosity may be necessary for trapping of sufficient O₂ for radiolytic production of O₃, as found for simultaneous irradiation and water vapor deposition producing such porosity. More work is needed, Loeffler et al. (2009) found that ion bombardment reddened a flat mineral sample even more than a porous sample.

Processes of surface sputtering, micro-meteoroid vaporization, and photon stimulated desorption, all potentially contributing to space weathering, can be partially identified and characterized by the measurement of the ion and neutral species ejected from sputtered surfaces. Any ion freshly produced at the surface, or from neutrals in the overlying exosphere, is immediately accelerated by local magnetospheric or ionospheric electric fields and moves rapidly to spacecraft altitudes for direct in-situ measurement. The sputtered neutrals can also either be directly measured to determine energy distributions and composition, or the resultant exospheric distributions can be measured with respect to global spatial coordinates and composition. It is usually rather simple to understand how the energy distribution of the neutrals is influenced by the environment of the planetary objects, so a measurement of the atmospheric energy distribution can allow determination of relative sizes of gravitationally bound and escaping components. For the heaviest molecular species, pickup ion detection may be the most sensitive, since the spacecraft orbit (e.g. at Europa) would be far higher than scale heights for these heaviest species. Composition and flux measurements for the ions and neutrals can in turn provide information on the bulk composition of the planetary object and on the resurfacing rate. *These sputtered particle measurements are examples of how space weathering should also be regarded for mission planning both as a science driver and as enabling for instrumentation.*

Extremely important for subtraction of the space weathering contributions to surface and exospheric composition is that the background source composition of the magnetosphere be measured at least as well as the surface and overlying exospheric composition. Plasma composition in the Jupiter and Saturn magnetospheres should largely reflect composition of volcanic outflows respectively from Io and Enceladus. Erosive space weathering, e.g. sputtering, injects other elemental and molecular species into the local magnetospheric environments of the source moons. *But we have little knowledge of the plasma composition in either system or*

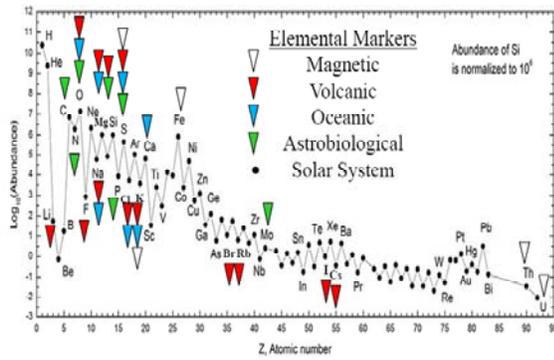


Figure 3. Solar system abundance of elements with markers for elements relating to key processes of high planetary science interest.

elsewhere beyond a few major species, and the enormous differences in the ion to neutral ratios in these magnetospheres are also not understood. Improvement of magnetospheric composition measurements to the full elemental (Figure 3) and isotopic level will inform us on internal chemistry of the sources while also defining the baseline exogenic contributions for the moon surfaces of those systems. If astrobiology and search for biosignatures, and precursors, continue to be major drivers for solar system exploration, then we *must* establish background reference baselines to guide the search for surface and exospheric anomalies indicative of such signatures. A prime example is the mass fractionation from sputtering and exospheric escape

that would leave heavier isotopes on an irradiated icy moon surface. Lighter isotopes, e.g. for carbon, could be used to locate freshly emergent material, potentially even biological.

For the ionic component of direct sputtering, a potentially overlooked but very important mechanism, is electron-stimulated desorption (ESD), e.g. Yakshinskiy and Madey (2001). This very well known process involves the excitation (often ionization) of a surface target followed by charge ejection, bond breaking and ion expulsion due to the resultant Coulomb repulsion. Though the role of electron stimulated desorption processes is not discussed much within in the planetary science community, the impinging energetic electrons that leak through the magnetospheres or reach the surfaces during flux transfer events may induce significant material removal. Given the energetics and the wide band-gap nature of the minerals on planetary bodies, the departing material may also be primarily ionic. *The role of 10 eV – 1 keV electron stimulated desorption and dissociation (ESD), along with keV-MeV electron radiolysis, could be significant.*

Finally, we must also consider impacts of surface irradiation on the electrostatic, magnetic, and electromagnetic field configurations at these surfaces. Static charge buildup can be driven by photonic and charged particle irradiation, and by triboelectric charging of dust particles in Enceladus-like cryovolcanic outflows. Potentials on the Moon have been observed from a few 10's of volts positive to tens of thousands of volts negative. Arc discharging might potentially be detectable via electromagnetic emissions and could transiently affect local chemistry, while also being a potential danger to in-situ surface experiments. On the Moon, dust levitation may be a significant source of surface alteration, while charged dust can rapidly lead to dust deposition and adhesion affecting robotic and manned surface operations. Charging of cometary dust may well be key to understanding plasma-dust interactions in the complex nucleus environment of a comet. Differential charge buildup (e.g. related to topographic variations in surface irradiation) may also lead to current flows (Gudipati et al., 2007) in near-surface micro-ionospheric environments of irradiated ices as a source of joule heating for activation of otherwise-inhibited chemical reactions, detectable emissions of electromagnetic radiation, and contributions to induced magnetic fields. Even asteroid surfaces (and the dusty surfaces of Phobos and Deimos) likely will be affected by charging. A consistent methodology for monitoring and modeling charging is required to understand and mitigate charging effects. *Assurance of reliable spacecraft and instrument operations in plasma charging and energetic particle radiation environments is a major cost driver for missions to planetary magnetospheric environments.*

Laboratory Measurements

Experiments in controlled laboratory configurations are crucial to interpretation and understanding of remote spectroscopic data for weathered planetary surfaces. The experiments must simulate key parameters of the space environments such as temperature, radiation environment, chemical composition (e.g. ices versus minerals), and ultrahigh vacuum conditions. Such experiments must be capable of mimicking target surface interactions of ionizing radiation (charged particles from the solar wind and galactic cosmic rays; solar photons) with low temperature ices and mixtures with silicates and carbonaceous matter. Examples of controlled parameters are: i) the chemical composition of the solid targets (water, ammonia, methanol, methane, silicates, carbonaceous matter), ii) crystalline and amorphous ices, iii) surface temperatures 10-550 K (Mercury to KBOs), iv) kinetic energy and composition of the charged particles, v) photon energy, and vi) cumulative effects of charged particles and photon interactions with ice/mineral surfaces. A key limitation is that sizes and thickness of samples are typically microscopic and not truly representative of real bulk samples, e.g. meters-thick impact regolith. Scattering nature of a thick sample makes optical transmission spectroscopy and other techniques difficult. *New facilities and techniques to acquire data from thick samples are needed.*

For thin film ices complementary detection systems must be interfaced so that newly formed atoms and molecules can be monitored in real time in the gas phase and in ices. By analyzing intermediates and products *on line* and *in situ*, the mechanisms of the formation of new species can be extracted as well. For the solid state, common detection systems are: i) infrared spectroscopy (detection of molecules via an excitation of vibrations which are associated with changes in the permanent dipole moment of the molecule), ii) Raman spectroscopy (monitoring vibrations of a molecule depicting a change in molecular polarizability of, for instance, homonuclear, infrared inactive diatomic species like molecular hydrogen, oxygen, and nitrogen), and iii) ultraviolet-visible spectroscopy (identification of electronic transitions in atoms and molecules, often radicals). Infrared and UV-visible laboratory data can also be useful for comparison with astronomical data, however more near-infrared (overtone of vibrations) laboratory data is needed for comparison to data acquired from orbiting spacecraft that routinely acquire data in this spectral region. Other techniques such as electron-paramagnetic resonance, fluorescence and x-ray spectroscopy could offer unique capabilities to identify radiolysis products in ices. Products released into the gas phase can be sampled via a quadrupole mass spectrometer (QMS) monitoring the complete product spectrum based on the mass-to-charge ratios of the ionized products (residual gas analyzer) or the velocity and hence kinetic energy of the products at a defined mass-to-charge ratio (time-of-flight mode). Products can be ionized via electron impact ionization or by tunable ultraviolet photons (selective ionization of structural isomers). The destruction efficiency of a molecule (the photodissociation cross section) depends strongly on the wavelength of the photon. *At present, no 'universal' detection scheme exists which can probe all products simultaneously in the gas phase and in the solid state.* However, careful combination of various analytical schemes can allow identification of atoms, diatomic, and polyatomic species.

Among the many complexities of space weathering simulation is that affected surfaces are in reality exposed simultaneously to particle and photonic energy sources. In the laboratory the products of these radiation components are usually measured separately, but these components may act in sequence to produce a substantially different result, e.g. higher sputtering yield when ion sputtering is followed by photon- or electron-induced desorption. It may then be difficult to pin down the reaction mechanism and to predict the chemical evolution of surfaces if we cannot distinguish if a product results from the photon and/or charged particle exposure. It is imperative

that all studies must be conducted in an identical experimental setup with exactly the same analytical devices to guarantee that all experimental conditions are well-defined and reproducible from experiment to experiment. A further limitation of restricted sample size is that simultaneous effects of the full range of particle and photon energies in incident spectra are not investigated.

Recommendations

Support comprehensive specification of space weathering environments through expansion of cooperation between NASA heliophysics and planetary science divisions on placement of environmental radiation instrumentation on appropriate missions, compilation of data and semiempirical models from measurements, and on predictive models for each environment.

Rationale: In the heliophysics community there is the concept of the Heliophysics Global Observatory (HGO), the collective fleet of operational heliophysics missions, that should be expanded for interdisciplinary applications to include planetary missions. Heliophysics support for space environment modeling, e.g. the Earth-Moon-Mars Radiation Environment Module (Schwadron et al., 2007) and earlier (e.g., NASA GSFC, JPL) models for solar and cosmic ray energetic particle modeling in the terrestrial planet domain, can be usefully applied to planetary interaction applications. Similarly, missions and data models for planetary interactions can also support investigation and modeling of interplanetary environments. HGO data virtual observatory approaches could be applied to planetary missions.

Encourage community-wide and interdisciplinary investigations of universal space weathering processes through balanced mixture of initiatives on mission instrument data analysis, laboratory measurements, computational modeling, and relevant theoretical investigations.

Rationale: The space environment is universal in the sense of connecting all the planetary environments, and so it most efficient to approach space weathering processes from the universal perspective, e.g. that similar processes act everywhere and the effects differ only in the relative energy deposition rates and compositional impacts of each process in different locations. Process investigations must be well-grounded in measurements for different environments, in broad-spectrum approaches to laboratory simulations, and best available inputs from theory and high performance computing.

Enable development of plasma ion, energetic particle, and neutral composition spectrometers for in-situ analyses to characterize elemental and isotopic range of interconnected planetary surface, atmospheric, ionospheric, magnetospheric, and heliospheric environments.

Rationale: Our knowledge of composition in these environments beyond the Earth is limited to some major species with little or no information on the full range of elemental and isotopic composition that is critical to determination of origins, evolutionary processes, and astrobiological potential. Sample return is too expensive for general application, advanced in-situ analysis capabilities being required for one-way missions to most non-terrestrial destinations of the solar system. There is also strong coupling of composition for these connected environments and this coupling should be considered in weighting the relative priorities of measurements in each environment.

Provide facilities for more realistic laboratory science and engineering simulations of planetary surface environments under simultaneous influence of extreme limits on pressure, temperature, radiation, composition, physical structure, and endogenic or impact activity.

Rationale: There are no truly flat surfaces, particularly when viewed at the microscopic level of most space weathering processes, and multiple energy sources are typically operating on affected surfaces. The sensible and accessible surfaces have impact regolith layers extending to meters in depth and likely with high porosity under conditions of reduced gravity. Multi-phase interactions of ice, grains, and volatiles in irradiated bulk surface samples need much further investigation with appropriate facilities. Engineering simulation facilities require development to support realistic and extreme environment testing for future orbital and landed missions to irradiated icy bodies such as at Europa, Ganymede, Enceladus, and Triton.