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Far-out surface science: radiation-induced surface processes in the solar system

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Abstract

Interplanetary space is a cosmic laboratory for surface scientists. Energetic photons, ions and electrons from the solar wind, together with galactic and extragalactic cosmic rays, constantly bombard surfaces of planets, planetary satellites, dust particles, comets and asteroids. Many of these bodies exist in ultrahigh vacuum environments, so that direct particle–surface collisions dominate the interactions. In this article, we discuss the origins of the very tenuous planetary atmospheres observed on a number of bodies, space weathering of the surface of asteroids and comets, and magnetospheric processing of the surfaces of Jupiter's icy satellites. We emphasize non-thermal processes and the important relationships between surface composition and the gas phase species observed. We also discuss what laboratory and computational modeling should be done to support the current and future space missions—e.g. the Genesis mission to recover solar wind particles, the Cassini mission to probe Saturn, the Europa Lander mission to explore the subsurface ocean hypothesis, and the Pluto/Kuiper Express to sample the outer reaches of the solar system. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

1.1. We are constantly being bombarded!

Interplanetary space is a cosmic, ultrahigh vacuum laboratory for surface scientists. The "space" between planetary bodies, and even the rarified atmospheres above a number of large bodies, correspond to much better vacuum than that generally attainable in laboratories. Although interplanetary space conjures up a mental image of a vast, peaceful void of total emptiness, in reality, it is a stormy and sometimes very violent environment permeated by energetic particles and radiation constantly emanating from the Sun. This outpouring from the Sun is called the *solar wind*, and is an expanding mixture of fully ionized gaseous material; i.e., an electrically neutral plasma containing electrons and ions that

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carries a magnetic field and constantly streams outward from the inner solar corona. In addition to the solar wind, photons, solar flare ions and cosmic rays bath the solar system, so that *most planetary and interplanetary surfaces are, in fact, continuously bombarded by radiation.* Mankind is rather fortunate since the magnetic field and atmosphere of Earth shield us surface inhabitants from the harmful effects of this continuous unfriendly assault!

The magnetic field of the Earth creates a magnetosphere that "funnels" most of the charged particles near the poles creating the great northern and southern light shows, i.e., the beautiful optical displays of the aurora borealis and aurora australis, respectively. A little farther from home, the photons from the Sun can cause our Moon to "glow" even during the daytime by stimulating the removal of alkali metal atoms from its surface. As we proceed beyond the outer reaches of the so-called traditional "habitable zone", we encounter the asteriod belt which is composed of a multitude of "minor" planets or, more simply, planetary fragments. On an unfortunate occasion, an asteriod can plummet towards the Earth (a scenario that Hollywood box offices find attractive and one that has been suggested to explain the extinction of dinosaurs). Asteriods that do not annihilate themselves by slamming into larger planetary objects are space weathered by radiation. The small interstellar ice grains and dust particles, which collectively account for much of the measurable mass of the universe, are also constantly "processed" by radiation. In the outer solar system, the magnetospheres of Saturn and Jupiter trap energetic ions and electrons that irradiate the low temperature ice present in the rings of Saturn and the rocky and icy material of Jupiter's satellites. The four major satellites of Jupiter are Io, Ganymede, Europa and Callisto. These spectacular objects were first observed by Galileo Galilei in 1610 and described in Sidereus Nuncius (Starry Messenger): *Magna longeque admirabilia spectacula pandens suspiciendaque proponens unicuique.* (Revealing the great and most spectacular display to everyone to contemplate.) The surfaces of these heavenly bodies are significantly altered by radiation bombardment!

1.2. The surfaces of interest

In this paper, we focus on bodies in the solar system which have tenuous atmospheres, comparable to ultrahigh vacuum (UHV) in the laboratory ($<1 \times 10^{-8}$ Pa). These include the planet Mercury, the Moon, the icy satellites (moons) of Jupiter and other satellites, asteroids, etc. In a recent article in Newsweek [1] entitled "Shoot the Moon", a headline trumpeted "with 66 Moons in the solar system, it's sheer lunacy out there—Moons with water, atmospheres or both are good places to discover how life on earth got started". For most of these bodies, thermal processes and direct particle–surface collisions dominate the surface interactions and lead to fascinating surface chemistry and physics, including the formation of tenuous, ballistic atmospheres (i.e., UHV atmospheres in which gravity is the dominant force affecting the trajectories of atmospheric atoms and molecules).

There is a wide and complex spectrum of materials whose surfaces are exposed to the space environment. Some of our earliest and most direct information about materials in space has literally fallen from the sky in the form of meteorites. Most are chondrites, iron-rich bodies containing silicates and ppm traces of most of the elements in the periodic table [2]!

The Moon is the only planetary body (besides Earth) for which rock samples have been collected from known locations, thanks to the Apollo Moon-lander missions. The lunar samples are predominately silicates, with SiO_2 as the dominant constituent. Other oxide components vary from location to location, and include Al_2O_3, MgO, FeO, CaO and TiO_2, with traces of Na_2O and K_2O [2]. Lunar Prospector maps of the Moon show the surface distribution of Fe, Ti, Th and K [3]. Optical reflectance studies of Mercury provide evidence for Mg silicates.

The cold planets (Jupiter and beyond) and the icy satellites of Jupiter are largely covered by layers of condensed molecules (e.g., NH_3, CH_4, H_2O, CO_2, $N_2, \ldots$) [2]. The icy satellites of Jupiter also contain large amounts of water ice and non-ice regions that may contain hydrated minerals (possibly from a subsurface ocean) and radiation-processed materials, including sulfuric acid.

Thus, the challenge to surface scientists is in the study of oxide surfaces, including complex multi-component minerals, and the surfaces of condensed molecular solids containing dissolved minerals. These are far more complex than the elemental solids and binary oxides typically studied in surface science laboratories!

2. The radiation environment

2.1. Solar photons and the solar wind

Solar photon radiation is by far the largest source of radiant energy for surface processing, and most of this energy is in the form of infrared and visible photons. Some of this energy is absorbed by objects in the solar system, and causes heating of the surface regions. In addition to possibly inducing equilibrium chemistry on exposed surfaces, the heating leads to thermal desorption of gases from a number of 'airless' bodies (see Section 3.1, below). Here we will primarily describe processes induced by more energetic radiation. For instance, solar photons with energies above ~4 eV can induce bond breaking causing stimulated desorption of absorbates. Higher energy photons and energetic charged particles can induce chemistry in surfaces causing, for instance, alterations in the reflectance properties, as well as desorption of bulk species. Finally, low energy electrons, in addition to being important for surface charging, can cause electronic excitations that lead to desorption These processes will be discussed in later sections. Table 1 lists the particle fluxes and the energy fluxes in a number of environments. These are elaborated on below.

The flux of energetic particles available for surface processing spans an enormous range of energies [4,5]. Surfaces in the interplanetary medium are exposed to the continuous expansion of the solar corona referred to as the solar wind (see Fig. 1), primarily consisting of ions representing the solar abundance of elements with flow energies ~1 keV/amu and a thermal distribution ~10 eV. A corresponding flow of electrons occurs also with similar thermal energies. This flux, given in Table 1, decreases like the solar photon flux as $\sim 1/R^2$, where R is usually given relative to the distance from the Sun to the Earth (1 AU, Table 1). Superimposed on this are more energetic particles associated with active regions on the Sun and solar flares (10's of keV to 10's of MeV) and the cosmic-ray background flux given in Fig. 2.

2.2. Magnetospheres of giant planets

Of current topical interest is the large flux of energetic ions and electrons trapped in the magnetospheres of the giant planets, roughly equivalent to Earth's van Allen belts. Our Moon lies outside the earth's magnetosphere for most of its orbit, and receives the full blast of the solar wind

Table 1
Radiation flux

Radiation	Flux ($\mathrm{cm^{-2}\,s^{-1}}$)	Energy flux ($\mathrm{eV\,cm^{-2}\,s^{-1}}$)
Solar photons (1 AU)[a]		(8.5×10^{17})
IR (<1.8 eV)	2×10^{17}	4.0×10^{17}
Visible (1.8–3.1 eV)	1×10^{17}	3.7×10^{17}
UV-A (3.1–3.9 eV)	2×10^{16}	7.2×10^{16}
UV-B (3.9–4.4 eV)	2.5×10^{15}	1.0×10^{16}
UV-C (4.4–12.4 eV)	1×10^{14}	4.3×10^{15}
EUV (>12.4 eV)	1×10^{10}	1.3×10^{11}
Lyman-α	3×10^{11}	3×10^{12}
Solar wind (1 AU)[a]		
1 keV/u H^+(96%), He^{++}(4%)[b]	4×10^{8}	4×10^{11}
electrons (~12 eV)	4×10^{8}	
Cosmic ray ions (see Fig. 2.1)	2	6×10^{9}
Magnetospheric plasmas		
Europa (9.4 R_J)[c] (see Fig. 2.2)	3×10^{8}	(8×10^{13})[c]
Dione (6.3 R_S)[d]	1×10^{12}	3×10^{12}

[a] Average solar conditions at 1 AU (distance from Sun to Earth) [83]; decay as R^{-2} with R in AU (e.g., Jupiter is 5.2 AU, Saturn is 9.54 AU).

[b] Other ions are approximately solar [83] or cosmic [82] abundance.

[c] Orbital distance in Jupiter radii (R_J). Flux is for ions; total energy flux includes energetic electrons [5]. Low energy plasma determines flux, high energy plasma determines the energy flux.

[d] Orbital distance in Saturnian radii (R_S). Flux and energy flux are for ions. Low energy plasma determines flux, high energy plasma determines the energy flux [69].

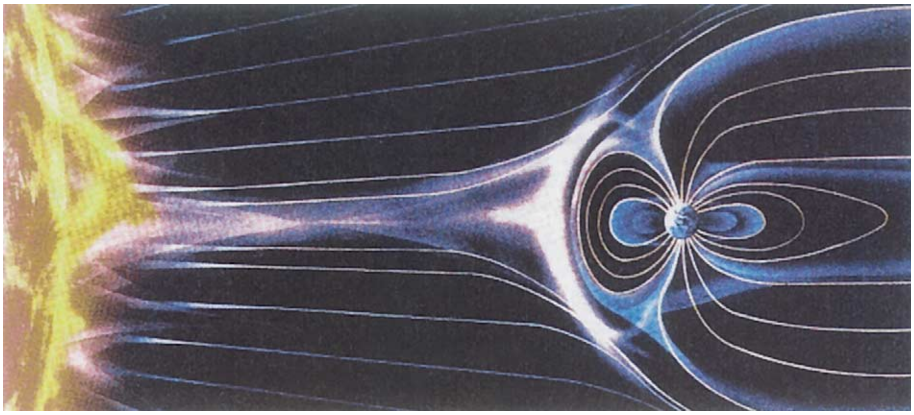

Fig. 1. Artist's conception of solar wind interacting with magnetosphere of Earth (not to scale!). From Rice University with permission.

during that time. However, for a few days around the time of full moon each month, the Moon passes through the earth's magnetotail and is largely shielded from solar wind particles. During the full moon, the Moon is exposed primarily to solar photons and cosmic-ray particles. In contrast, many of the moons and ring particles of the giant planets lie within their magnetospheres. Therefore, they are exposed to the flux of trapped ions and electrons. The charged particle energy flux to the surface given in Table 1 is larger than the chemically interesting UV flux (photons $> \sim 6$ eV) when scaled to Jupiter's distance from the Sun. In fact, on most of the large moons in the outer solar system, (with the exception of Titan, which has an atmosphere larger than the Earth's), the surfaces are altered by the trapped particle radiation. This radiation environment has been measured by the Pioneer, Voyager and Galileo spacecrafts.

Whereas the trapped plasma data for Saturn, Neptune and Uranus are sparse, the Jovian environment is well described. In Fig. 3 is given a recent description of the energetic particle flux at Europa [6]. It is seen that the energetic electron and proton fluxes dominate, but there is also a large flux of multiply-charged oxygen and sulfur ions. The mass spectrum of trapped magnetospheric ions at Europa is seen to be very different from that for the solar particles and the cosmic rays (e.g., Fig. 2). This indicates that the sulfur and oxygen ions, and probably also the protons, are produced and accelerated within Jupiter's magnetosphere. In fact, principal sources of the ions in the giant planet magnetospheres are the surfaces of the imbedded moons and ring particles, indicating the surface processing of these bodies is self sustained. In addition to the energetic ions, a flux of lower energy ions (referred to as thermal plasma) can flow onto the surfaces of the Moons and the ring particles. Because of the rapid rotation of the Jupiter's magnetosphere and the distance to the Galilean moons these particles (mainly H^+, O^{n+}, and S^{n+}) have energies of 100's of eV to $\sim$10 keV and are important for sputtering but constitute a smaller energy flux than for the energy range in Fig. 3. Similar energetic plasmas are trapped in the magnetospheres of the other outer planets [4] as indicated in Table 1 for Saturn.

Whereas the cosmic-ray particle bombardment is isotropic, the solar wind and the trapped magnetospheric particle radiations are not. The geometry of the bombardment is shown schematically in Fig. 4 for Europa. Jupiter's icy moons, like our Moon, are phase-locked to the parent planet. Since they rotate around Jupiter slower than Jupiter's field rotates, the trapped plasma flows preferentially onto the hemisphere trailing the motion [4]. In addition, the moon Ganymede has an intrinsic magnetic field, one of the great discoveries by the Galileo spacecraft. This filters

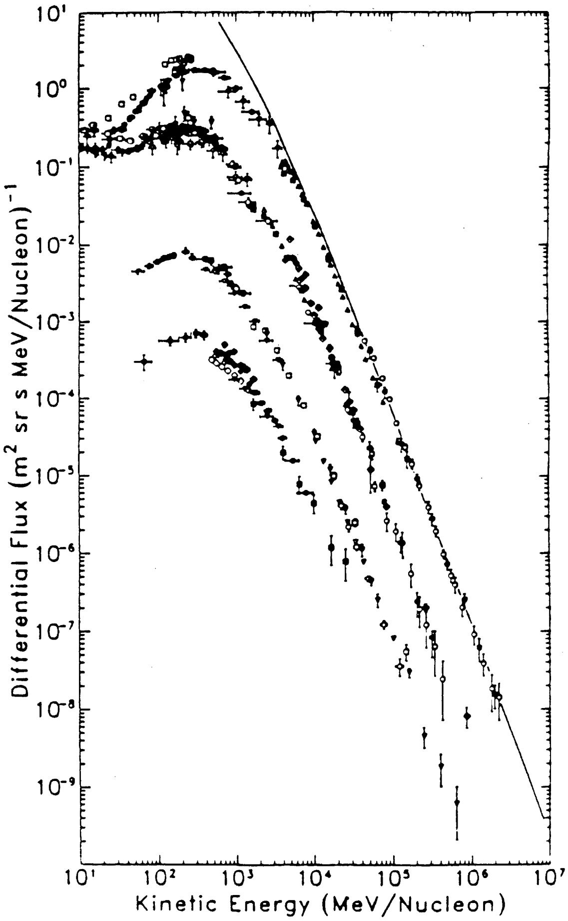

Fig. 2. Summary of energy spectra data measured at Earth for the cosmic-ray ion flux versus ion energy, expressed as MeV per nucleon. The four sets of compiled data are for the elements, hydrogen, helium, carbon and iron in order of decreasing flux. The solid line indicates the total proton energy spectrum extrapolated to the interstellar medium after correcting for solar modulation [82]. That is, the Sun's magnetic field deflects the low energy galactic protons, so the corrected spectrum corresponds to protons incident on objects in the distant reaches of the solar system (e.g, the Oort cloud).

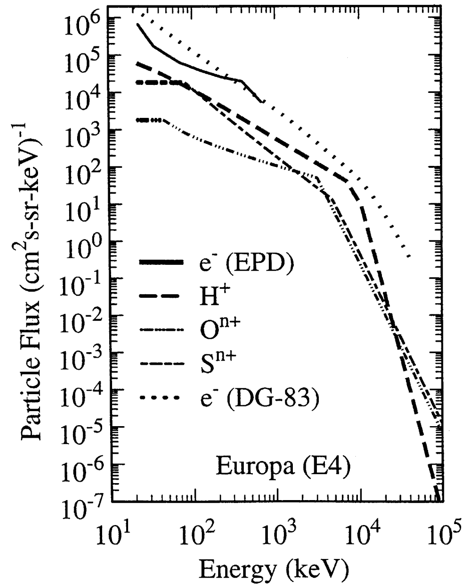

Fig. 3. Energy and mass spectra of energetic charged particles, H^+, O^{n+} and S^{n+} incident on Europa, measured by Galileo (from Ref. [6] with permission).

the particles that have access to the equatorial regions leading to preferential bombardment of the poles. Indeed, weak polar auroras are seen due to surface sputtering. Therefore, there are important spatial differences in the radiation flux to the surface that can be useful in trying to understand the surface processing. For example, the reflectance spectrum of the leading and trailing hemispheres are seen to be different, which has long been a rationale for studying the radiation processing of these surfaces [4].

Model calculations have been made of energy deposition into the surface layers of Europa. Weakly interacting protons and electrons affect the surface well below the typical optical depth on time scales are much shorter than typical geological time scales ($\sim 10^7$ yrs on Europa). Further, the heavy ions (O^{n+}, S^{n+}) interact strongly with the surface (low penetration) depositing very large amounts of energy in a small layer (<0.1 μm) in very short times. Adding to this the energy deposited by the 'thermal' plasma flux suggests that near surface materials could be fully decomposed on a stable surface. Whereas geological processes are very slow, surface fragmentation and stirring by micrometeorites occurs on comparable time scales but preferentially on the hemisphere leading the motion. These spatial differences allow the possibility of separating surface weathering effects. Below we describe the effects of thermal heating and particle bombardment on the surfaces of solar system materials.

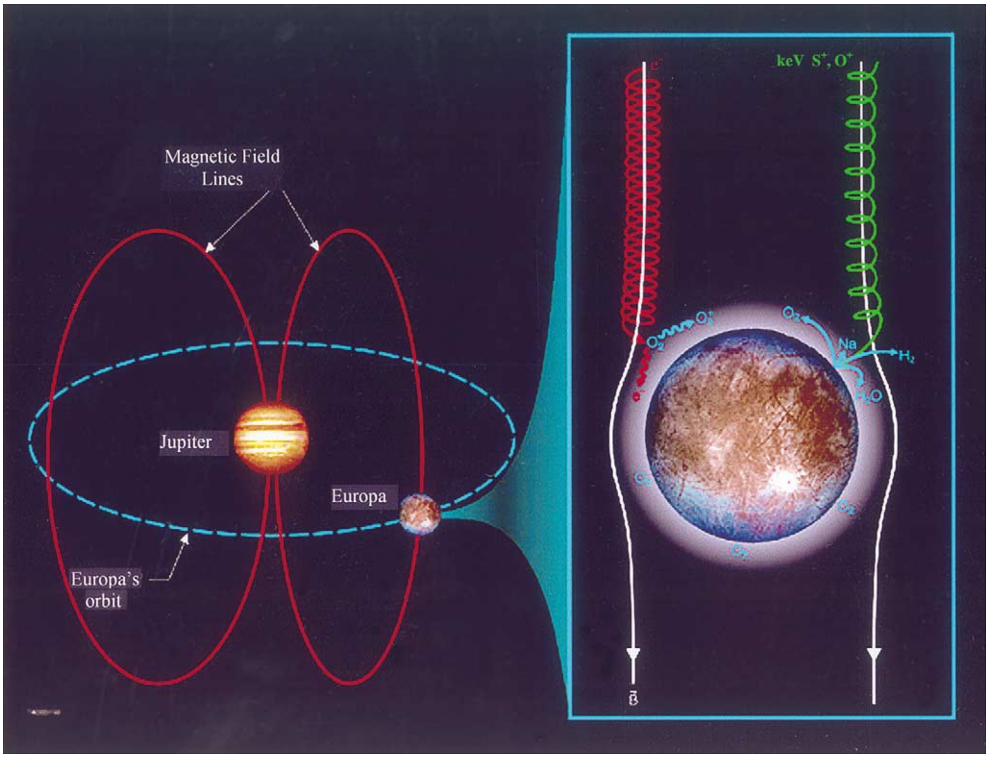

Fig. 4. Schematic of interaction with the magnetosphere. Left hand side, Europa and magnetic field lines rotate around Jupiter at different speeds. Right hand side, energetic ions and electrons moving along the field lines can sputter and decompose the surface, producing a tenuous atmosphere and ionosphere.

3. Relevant surface phenomena

3.1. Thermal processes and desorption from surfaces

The temperature extremes due to weather on Earth, from the coldest night in Antarctica to the hottest day in the Sahara, range from roughly 200 to 330 K. Much greater temperature extremes are experienced in the solar system due to the presence (or absence) of a flux of solar infrared photons, especially on surfaces that are not protected by an atmosphere. Solar heating at "noontime" at Mercury's equator causes surface temperatures of ~700 K, while the side of Mercury away from the Sun cools to ~100 K (due to radiation losses) during the long night. The lunar subsolar point (i.e., the equator at high noon) reaches ~400 K, while the darkside of the Moon is ~100 K. The extremes of temperature (and the swings in temperature) mean that thermally-induced surface chemistry, especially thermal desorption of surface species, is constantly occurring. Thermal desorption refers to heating of a substrate and the accompanying desorption or evaporation of surface species [7]. The temperature at which an atom or molecule desorbs from a surface is directly related to its bond strength or adsorption energy to the surface [8].

Surface science studies of thermal desorption of atoms and molecules from oxide surfaces, and of desorption from condensed gases, can provide insights into thermal processes that affect the weathering and atmospheres of solar system bodies. At 700 K, for example, the desorption rate of alkali atoms (Na and K) from a silicon dioxide surface is considerable; this suggests that thermal processes may contribute to the Na and K in the tenuous atmosphere of Mercury [7]. The Na and K may then adsorb on the cold side, and be released again as the planet rotates to face the Sun. Whereas water ice has a very low vapor pressure at 150 K ($\sim 10^{-4}$ Pa), nonetheless, this corresponds to a vaporization or desorption rate of ~ 1 monolayer/sec. On geological time scales, H_2O vapor can be transported from "warm" to "cold" regions on icy satellites, and may be responsible for changes in observable surface features on Ganymede. Thermally-driven sublimation and condensation of small molecules must occur constantly at the surfaces of all the outer planets and their icy satellites.

The role of thermal desorption phenomena on interstellar "space dust" is considered in the article by Williams and Herbst, also in this volume [9].

Despite the importance of thermal processes in explaining some aspects of weathering, tenuous atmospheres, etc., there are many phenomena that cannot be explained by thermal effects alone. As indicated above, non-thermal radiation effects (e.g., bombardment of surfaces by energetic solar photons, the solar wind, and planetary magnetospheres) play a dominant role in interplanetary space.

3.2. Energetic particle/solid interactions

For eons, the surfaces of lunar soils, interplanetary dust particles, asteriods, comets and icy surfaces have been bombarded by macro- and microscopic meteorites, galactic and extragalactic cosmic rays, solar ultraviolet photons, and solar wind and flare ions as discussed above. These impact events can result in physical (structural) and chemical (compositional) changes which are observable using ground based and orbital telescopes and spacecraft (i.e. Voyager, Hubble Space Telescope, International Ultraviolet Explorer, Galileo, etc). The process of bombardment-induced surface alteration or damage has been coined "space weathering"—a term that has been borrowed from the geological processes of erosion and degradation on earth caused by air and water.

Though much of the material removal and the chemical alterations due to space weathering happen over geological time frames and distances*, the physical and chemical basis for important material removal and alteration processes involves atomic and molecular collisions and electronic excitations in the surface material.* It is well known that the slowing down of energetic particles is due to the interaction of the colliding entity with the atomic nuclei and electrons in the target material. For the relevant incident ions and photons described above, the production of excitations and ionization are the principal mode of interaction. In fact, the surface science community has studied these type of interactions for decades and a detailed understanding of the principles of collisional sputtering as well as electronically-induced sputtering or desorption induced by electronic transitions (DIET) [10] has emerged.

Some definitions of experimental methods used by surface scientists to study radiation-induced desorption of atoms, molecules and ions from surfaces are appropriate here. DIET includes photon-stimulated desorption (PSD) as well as electron-stimulated desorption (ESD). PSD refers to the desorption of atoms or ions as a result of a direct photon-induced electronic excitation of a surface species, such as a bandgap excitation, a valence electron excitation, or a core excitation [11]. Solar photons can be responsible for PSD. ESD refers to desorption initiated by an electronic excitation during electron bombardment of a surface [12,13]. For surfaces in space, the electrons may originate in the solar wind, or the magnetosphere plasma, or they can include secondary electrons released when the substrate is bombarded by photons or ions. The manifold of electronic excitations that lead to desorption in ESD and PSD is nearly the same in most cases, although there are differences in cross-sections and energy dependencies. Electron and photon bombardment can also produce alterations in surface chemistry.

Secondary ion mass spectrometry (SIMS) refers to bombardment of surfaces by ions (e.g., H^+, He^{++}) and the accompanying collision-induced sputtering of secondary ions from the target surfaces. The mass distribution of sputtered ions (as measured using a sensitive mass spectrometer) is a diagnostic of the surface chemical composition. For surfaces in space, the bombarding primary ions can include energetic ions in the solar wind, cosmic rays, or magnetospheric plasmas (cf. Table 1 and Fig. 2).

In one interesting collisional-sputtering experiment, Elphic et al. [14] simulated the influence of solar wind ions on the lunar surface in a laboratory SIMS study. They bombarded lunar soil simulants with 1.5 keV H^+ and He^{++}. While these ions are not efficient sputterers, significant fluxes of secondary lunar ions were seen, including Na^+, Mg^+, Al^+, Si^+, K^+, Ca^+, Ti^+, Mn^+, and Fe^+. The authors predict that fluxes of ions should be measurable from a detector in a 100 km lunar orbit.

In this article, we describe some advances and recent joint studies between planetary scientists and surface scientists which not only explain some remarkable observations, but which also reveal important aspects of radiation-induced surface processes on targets such as lunar soil surrogates, minerals, silicate particles, and ice—the "rock" of the outer solar system.

4. Some radiation-induced surface processes in the solar system

4.1. The origin of the Moon and Mercury glow

It has been shown that space weathering on the Moon involves high velocity and large momentum impact events (e.g., bombardment of the surface by micrometeorites—a form of "space dust" in the solar system). These result in the production of a melt and vaporization. Subsequent re-deposition of material produces "optical" coatings containing submicron sized particles of reduced iron. Photon and charged particle interactions with the lunar surface do not appear to control the lunar optical properties. However, non-thermal desorption of alkali atoms has been shown to contribute to the "glow" observed from our Moon and Mercury.

In the mid to late 1980's, neutral sodium and potassium vapor were discovered in the ultrahigh vacuum atmospheres of Mercury and the Moon [15–17] (Fig. 5). This was a surprise: Na and K are both very reactive atoms, and they are not observed in dense atmospheres. Both Mercury and the Moon have tenuous ballistic atmospheres (density too low for significant numbers of atom–atom collisions), and neither can retain Na or K for more than a few hours: the neutral Na and K are lost via photoionization by solar photons, and by readsorption. The atmospheric Na and K must be continuously resupplied, and the mechanisms proposed all involve surface processes [7,18–20]. Suggestions include collisional sputtering by the solar wind ions, thermal desorption, PSD, ESD, and micrometeorite impacts. Until recently, there were few data and no general agreement about which processes dominate. New results have shed light on this phenomenon: in laboratory UHV measurements, the photon-stimulated desorption of Na atoms from SiO_2 surfaces that simulate lunar silicates has been reported [21]. Bombardment of such surfaces at temperatures of $\sim$250 K by ultraviolet photons (energy > 4 eV, wavelength $\leqslant$ 300 nm) is found to cause very efficient desorption of Na atoms. Desorption is induced by electronic excitations (i.e., a photo-induced charge transfer) rather than by thermal processes (Fig. 6). The flux at the lunar surface of ultraviolet photons from the Sun is adequate to insure that PSD of sodium contributes substantially to the Moon's atmosphere [22]. On Mercury (as indicated in Section 3.1) solar heating of the surface is high enough that thermal desorption will also be a potential source of atmospheric sodium.

Where does the Na (K) come from? The small natural abundance is depleted via PSD at an approximate rate less than 1 monolayer per month but much of it is readsorbed (recycled); the surface Na(K) may also be restored by diffusion from the bulk, as well as by micrometeorite impact [23,24].

4.2. Surface charging in space

There is nothing neutral about objects isolated in a space environment: they invariably charge to a floating electrostatic potential that is determined by the balance between incident and emitted charged particles. Solar photons together with electrons and ions in the solar wind are the dominant bombarding species outside the planetary magnetospheres; photoemitted electrons and electrons created by secondary emission are the dominant charged species emitted from the surface

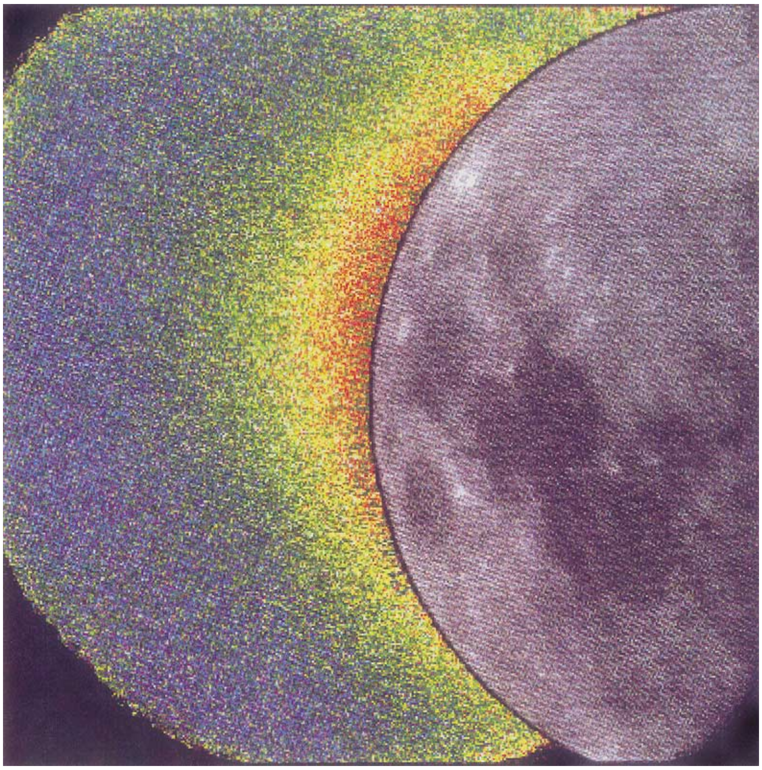

Fig. 5. Image illustrating the sodium vapor atmosphere of the Moon. The solar radiation is incident from the left, and the false color "haze" represents a high resolution spectrographic image of Na D-line emission (589 nm) due to sunlight scattered from Na atoms. The bright region just above the Moon's surface on the left (the "equator") is the region of highest Na vapor concentration. The Na emission is detected out to >10 lunar radii [20,23]. This image is from A.E. Potter, with permission [17].

[25,26]. At the Moon the sunlit hemisphere charges up to 20 V positive, mainly due to photoemission by ultraviolet photons [27]. The lunar terminator and nightside can have large negative potentials, -100 and -1000 V, respectively [28]. Small objects such as dust grains on the surface of larger objects, such as the Moon and Mercury, may become positively charged. These dust grains are repelled by the positively-charged Moon and can become levitated above the surface; there have been multiple reports of dust grains suspended above the lunar surface [29]. Charging of grains in Saturn's magnetosphere [30] is sufficient to affect the orbital dynamics of small grains and hence, the spatial morphology of Saturn's E-ring [31].

The photoelectric charging of dust particles in vacuum was recently tested experimentally using a simple apparatus [26]. The authors measured the ultraviolet light-induced charging of individual 100 μm—diameter grains of various particles, including glass and several metals. Insulating glass particles were clearly shown to be positively charged due to ultraviolet photoemission. The sign and magnitude of the net charge on the particles could be affected by their falling through a photoelectron "sheath" above a low work-function surface.

4.3. Space weathering of asteroids and comets

Most planetary scientists now believe that asteroids are remnants of a planet that was fragmented, and that asteroids are the "parents" of meteorites. Though it has been long suspected that a spectral signature could provide a link between asteroids and meteorites, the evidence for surface

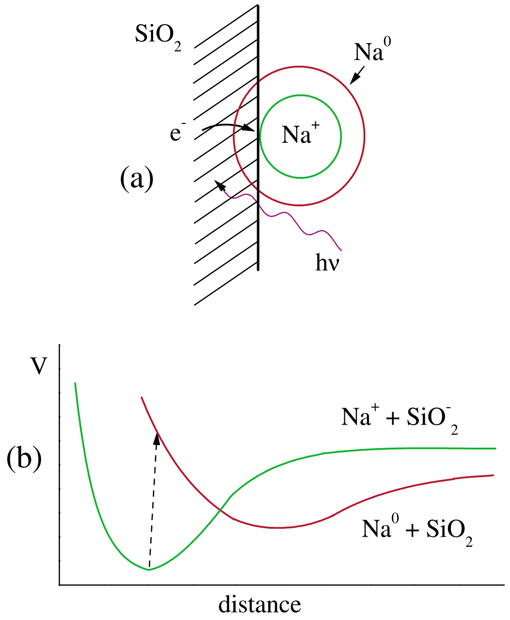

Fig. 6. Schematic mechanism for PSD of sodium from SiO_2, a model mineral for the lunar surface: (a) The sodium at the surface is ionic Na^+; a solar ultraviolet photon excites an electron in the substrate which attaches to the Na^+. This charge transfer converts Na^+ to neutral Na^o. Because Na^o has a larger radius than Na^+, the atom is in a repulsive state and can desorb (see (b) schematic of interaction potential V as a function of distance from the surface). This process is described in Ref. [21].

alterations and space weathering of asteroids (as seen in reflectance spectra and Galileo images of asteroids) may make this connection somewhat tenuous [32,33]. To test these, recent laboratory simulations of micrometeorites and solar wind irradiation of olivine, a major constituent of ordinary chondritic meteorites and S-type asteroids [2] show rather dramatic chemical alterations of the surface [34]. These alterations seem to change the optical reflectance in the near infrared and visible regions and may account for the optical differences observed in telescopic and remote observations of S-type asteroids and the bulk properties of collected ordinary chondritic meterorites.

Comets are composed of material left over from the formation of the Sun and planets and both observations and models indicate the presence of a large number of comets in the Kuiper belt and Oort Cloud. The Kuiper belt is located several thousand astronomical units away from the Sun and is considered to be the source of many short period (<200 years) comets, whereas the Oort Cloud at 10^4–10^5 AU is the source of the longer period comets. A limitation on the direct observations of comets in the outer solar system is the low optical albedo for reflection. It has been suggested that bombardment with galactic cosmic-ray particles, ions, and electrons and radiation-induced processing of hydrocarbons on the comet mantle surface leads to the general darkening. Though this mantle material is darkened, the subsurface and core (nucleus) is ice-rich and porous. Far ultraviolet images of comets like Hale–Bopp taken by the Midcourse Space Experiment spacecraft reveal huge clouds of atomic hydrogen and oxygen around the comets. These clouds can span many millions of kilometers and the strength of the Lyman alpha emission at 121.6 nm reveals a source term of 10^{29} hydrogen atoms per sec. The velocity of this gas is 8 km/s, about 10 times faster than the velocity expected for sublimation. Although radiation-induced surfaces processes have not been implicated as the hydrogen and oxygen source term, surface science studies have shown that electronic excitation of ice will produce hydrogen and oxygen atoms with non-thermal velocity distributions [35–37]. However, it has been suggested that "weathering" of comets at large distances from the Sun and cometary grain evolution are enhanced by "surface radiolysis" (i.e., radiation-induced changes in the surface chemistry) [38] and that many of the large organic molecules seen in the gas phase are produced by stimulated desorption [39].

4.4. Radiation processing of icy satellites: the Jovian system

4.4.1. Background; evidence for oxygen

Information on the icy Galilean satellite surfaces comes primarily from ground based and Earth-orbital telescopes, two Voyager flybys and the recent Galileo Jupiter mission flybys. As a result of these successful activities, one of the most exciting current research areas in planetary science is the study of the composition and chemistry of the Galilean satellites, Io, Europa, Ganymede and

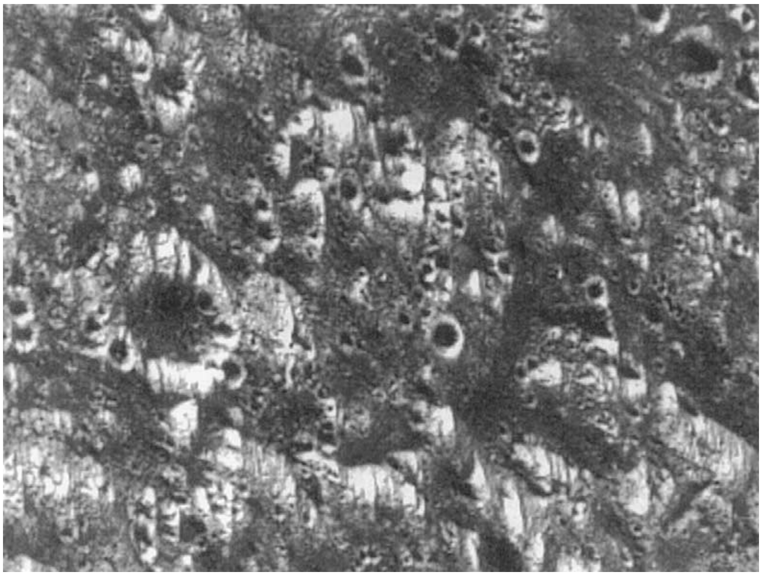

Fig. 7. This view of the Galileo Regio region of the surface of Jupiter's moon Ganymede shows details of the dark terrain that makes up roughly half of the surface. Dark areas may have originated from dark material released during meteorite impact. One of the many ancient impact craters is shown on the middle of the left. The image was taken on June 27, 1996 at a range of 7.625 km. Photo is courtesy of NASA/JPL/Caltech, from web site: http://www.jpl.nsa.gov/galileo/ganymede/p47066.html.

Callisto (Jupiter has 17 satellites, and these are the largest). Io, the first large satellite, is the most volcanically active body in our solar system. Europa is the second large satellite and has a dense core and an ice crust which may be "floating" on top of a liquid subsurface ocean. Ganymede, the third body, is also differentiated with scars from multiple meteorite impacts (Fig. 7) and Callisto, the fourth large satellite, seems to have also suffered many impact events and was recently suggested to have a subsurface ocean.

These satellites are located in the region of the solar system where low temperature water and other "volatile" species either stick to the surface or are trapped in the ice and mineral matrices for extremely long periods—nearly the age of the solar system. Therefore, a chemically interesting and rich mixture exists which may provide a unique window concerning the evolutionary processes that have occurred over eons of time. In addition, Jupiter's magnetosphere supplies a large dose of energetic electrons and ions to the surfaces of these moons as described above, which can lead to sputtering, material implantation, and radiolysis. Motivated by the Voyager data, extensive early experiments by Brown, Lanzerotti and co-workers [40,41] showed that the sputtering rates of ices by energetic ion and electron bombardment are comparable to the sublimation rates [4]. More recently, UV photon-stimulated desorption was shown to be efficient [42]. This bombardment can also lead to the formation of molecules, some of which may be of biological relevance. For example, the signature of condensed O_2 has been reported in the optical reflectance measurements of Ganymede [43] and oxygen atmospheres have been observed at Europa and Ganymede [44]. This was predicted based on laboratory studies which showed that low temperature water ice is efficiently decomposed and sputtered by ionizing radiation [45]. Whereas the excitations and ionizations lead primarily to radicals, the mass spectrum of ejecta was shown to be dominated by the most weakly bound species, H_2 and O_2, and well as H_2O [41,46]. Since the H_2 readily escapes to space and the H_2O recondenses, the O_2 is seen to be the primary species in the ambient gas. Whereas the early experiments demonstrated that O_2 is produced in

DIET processes by fast ions, it was also shown to be produced very efficiently under normal sputtering by lower energy ions [47].

Recently, a group of surface scientists examined the role of low energy electrons in the production of O_2 from low-temperature (<150 K) water-ice [48]. An "image" of the O_2 yield as a function of electron-beam spot position on a thin ice sample is shown in Fig. 8. Regions selected to spell out "O_2" were exposed to a 10^{15} cm^{-2} dose of 50 eV electrons at a sample temperature of 120 K. After this exposure, the electron beam was then rastered over the sample, and the O_2 yield was measured as a function of the electron beam spot position. The bright and dark areas correspond to high and low O_2 yields, respectively. This electron "write" and "read" experiment demonstrated a two-step "precursor" dissociation mechanism which is schematically illustrated in Fig. 9. Briefly, a water molecule is first excited by an electron, ion or photon impact. Since small changes in the ice structure or dynamic relaxation can cause the excited state lifetime to increase with temperature, the dissociation probability might also be expected to increase. The dissociation fragments of water (H or OH) can reactively scatter to produce a stable precursor molecule, possibly HO_2 or H_2O_2. A second electronic excitation then directly dissociates this precursor to form O_2, which can desorb.

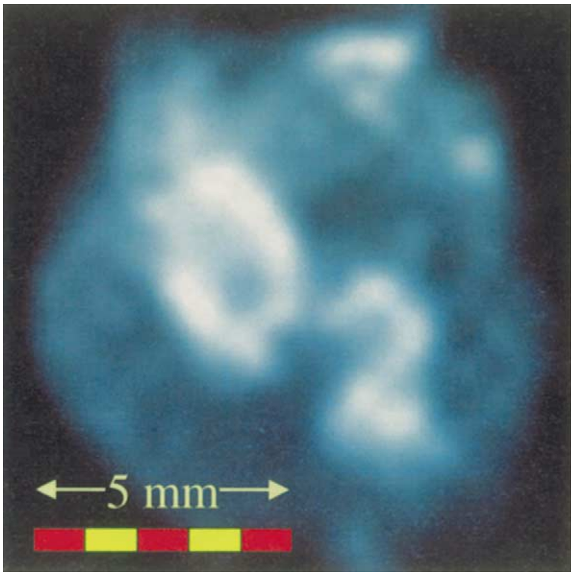

Fig. 8. An "image" of the O_2 yield as a function of electron-beam spot position on a thin ice sample. Regions selected to spell out "O_2" were exposed to 10^{15} cm^{-2} dose at 50 eV at a sample temperature of 120 K. After this exposure, the electron beam was then rastered over the sample, and the O_2 yield was measured as a function of the electron beam spot position. The bright and dark areas correspond to high and low O_2 yields, respectively. The circular profile of the sample is evident. (Copyright release from Ref. [48]).

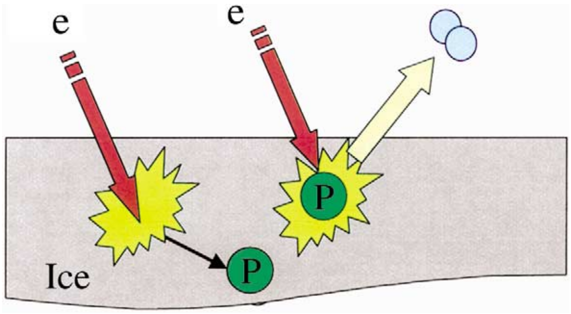

Fig. 9. Proposed scheme for the production of molecular oxygen on icy satellite surfaces which involves radiation-induced production of a precursor species, P, presumably HO_2 or H_2O_2, followed by radiation-induced production of O_2. The temperature dependence of the yield of O_2 is in the first step.

The mechanism proposed above is applicable to electronic excitations caused by essentially any radiation source and evidence for oxygen has been seen on a number of icy moons. One possible piece of evidence is the set of observations which suggests there is an absorption band close to that of O_3 on Ganymede and the icy Saturnian satellites [49]. Although O_3 is not firmly identified and is not a direct product of irradiation of ice, it is possibly formed after the accumulation of O_2 in some condensed form [50,51]. However, the strongest piece of evidence that the icy surfaces are being processed is the recent observation of H_2O_2 in the ice of Europa [52] and of other icy satellites. These observations are all consistent with the production and desorption of H_2 leaving behind an oxidizing surface [4,6]. Whereas the atmospheres of Europa and Ganymede contain radiolytically produced O_2, that of Callisto has predominantly CO_2 [53]. This may be due to slow outgassing of a primordial gas, but has also been suggested as a radiation decomposition product [54].

Finally, we note there are recent reports of excited H and O in the tenuous atmosphere of Europa, and excited O has been seen near the poles of Ganymede. Whereas the authors of this work [44,55] suggest that the excited species originate from impact excitation of sputtered water molecules (a gas phase process), it is possible that direct desorption of these excited species may be caused by radiation incident on the icy surface.

4.4.2. NIMS observations and implications for surface composition

Some of the most spectacular images of the satellite surfaces have been obtained using the Near Infrared Mapping Spectrometer (NIMS) onboard the Galileo spacecraft. The NIMS measures reflected light from surface zones ranging from about 1 to several 100's of kilometers in size. (Slightly larger than typical surfaces studied by conventional surface science techniques!) The spectrograph records 408 spectral channels between 0.7 and 5.2 μm and emphasizes a spectral regime that is dominated by vibrational overtone and combination bands of water ice. Distortions in certain bands have been correlated with the disrupted regions on the surface of Europa (see Fig. 10) and it has been suggested that the material associated with these disrupted regions are hydrated salt minerals such as epsomite ($MgSO_4 \cdot 7H_2O$), mirabilite ($Na_2SO_4 \cdot 10H_2O$) and Natron ($Na_2CO_3 \cdot 10H_2O$). Such materials were predicted from models for formation of these objects and are consistent with possible cryo-volcanism and injection from a subsurface briny ocean [56,57]. These materials have been shown to be stable under Europa's environmental conditions [58]. The possibility of a briny ocean, also suggested also by the Galileo magnetometer measurements [59], is very intriguing since it is an environment which could harbor very primitive life forms.

Recent work has suggested that these NIMS bands can instead be interpreted in terms of the presence of hydrated sulfuric acid [60]. This material could be produced by radiolysis of water and sulfur bearing species, or, less easily, by the decomposition of the sulfate salts discussed above [4]. The presence of hydrated sulfate ions and sulfuric acid is also consistent with the spectral signatures in the UV and visible of small amounts of SO_2 and S_x. Though the radiation chemistry leading to the production of sulfuric acid from one of the metal sulfates above is complicated and the yields are low, a reasonable buildup could occur over geological times [60]. Although a surface containing hydrated sulfuric acid might initially appear to be less-than-inviting for life, it along with the other surface oxidants can be a source of energy if subducted into the proposed ocean [6,61]!

4.4.3. Related observations

The discovery of gas-phase sodium atoms in the tenuous atmosphere of Europa [62] provides evidence that radiation-induced decomposition of the surface is ongoing [54]. Desorbed Na atoms that do not escape can be readsorbed in the predominantly icy regions of Europa. There are recent laboratory reports that ESD and PSD can efficiently desorb neutral alkali atoms from the surfaces of alkali-covered thin H_2O ice films (simulating the icy surface of Europa) [63]. The appearance threshold for desorption of K atoms is $\sim$4 eV, and is expected to be similar for Na. The proposed mechanism of desorption is an electronically-excited charge transfer from ice to alkali ion, followed by desorption (similar to the mechanism suggested for PSD of Na from the Moon [21]). We suggest that along with sputtering by energetic magnetospheric ions [54], ultraviolet solar photons and electron fluxes with $E > 4$ eV may cause alkali metal desorption from Europa's surface.

A number of other radiation effects have been proposed but are less well established. Differences in the reflectance between the leading and trailing hemispheres [64] have been seen on all of the large icy satellites of Jupiter and Saturn. The observed difference in reflectance between the poles of Ganymede and its surface at low latitudes has also been attributed to differences in the radiation environment [6] as discussed earlier. In addition, the presence of trapped CO_2 and SO_2 on on Europa, Ganymede and Callisto and a CO_2 atmosphere on Callisto may be due to radiation induced decomposition and sputtering [4,56,60]. In fact, based on the energy flux to the surface described earlier the ambient gas over the surface of Europa should contain additional sputtered material. If organics are present on the surface this could include large

Fig. 10. False color Galileo image of the icy plains and disrupted terrain on Europa. The plains are represented by the gray and blue regions and the mottled terrain is represented by patchy brown regions toward the left. Also visible are numerous linea which exhibit the same reddish-brown color as the disrupted mottled terrain. This brown color represents the presence of non-ice materials. Photo is courtesy of NASA/JPL/Caltech, from web site:http://www.jpl.nasa.gov/galileo/ganymede/p47906.html.

organic molecules as seen in SIMS experiments on organics in the matrices. On volcanic Io the surface materials are continuously replenished and are primarily coated in frozen volcanic SO_2 [65]. Color variations between the equator and the poles have been suggested as due to radiation-induced surface processing of the SO_2 [66] and the loss of Na from the surface has also been suggested as due to decomposition and sputtering of the surface [67,68].

It must be remembered that the NIMS sampling depths are only on the order of sub-micrometers to millimeters so the reflectivity measurements only sample the surface. Also, many of the bands are broad, the spectra are affected by the local chemical environment, and the surfaces are typically porous regoliths. Thus, the answer or "resolution" to the questions concerning the identification of the materials and chemical compositions present on planetary surfaces and interstellar media will rely heavily upon collaborations with the surface science community!

4.5. Radiation processing of the icy satellites: Saturn and beyond

4.5.1. Saturn's icy satellites and ring particles

Like the large moons of Jupiter, the surfaces of the icy satellites of Saturn as well as Saturn's ring particles are eroded and modified by the plasma trapped in Saturn's magnetosphere. This is a self-sustained process, as the predominant source of this plasma is the surfaces of the Moons and ring particles that orbit within the magnetosphere [69]. Whereas the density of particles in Saturn's main rings is high and the plasma formed is rapidly quenched, the spatially largest ring in the solar system (Saturn's E-ring) co-orbits with the icy satellites and is imbedded in the hot trapped plasma. This is composed of ~ 1 μm grains whose orbital motion is determined also by their surface charge in the ambient plasma. It is this charging that is thought to cause the large ring's spatial extent [31].

The surfaces of these ring particles and of the icy satellites serve as sputtering sources that produce a giant torus of neutral gas and plasma [4,69]. Quite remarkably, the OH component of the sputtered neutrals has been imaged by the Hubble space telescope and shows that, unlike Jupiter's magnetosphere, the ambient density of neutrals is larger than the plasma density [70].

The direct observation of the principal sputter product (OH from H_2O dissociated in the gas phase) along with the observations of trapped O_3 like [49] and H_2O_2 like [52] features in UV reflectance of the moons indicate that radiation processing of the surface materials is occurring. Since these satellites are phase-locked to Saturn there are also leading–trailing hemisphere asymmetries in the reflectance, with the more heavily bombarded side being redder in the visible [71].

4.5.2. Uranus, Neptune and Pluto

With increasing distance from the Sun more volatile species condense out and form components of the surface [65]. In fact, because of its relatively large cohesive energy, water ice is often thought of as the "rock" of the outer solar system with CO, CO_2, CH_4, N_2, and NH_3 forming the possible gases and condensates.

Uranus and Neptune each have a number of icy Moons but of interest typically are the largest ones, (Miranda, Ariel, Umbriel, Titania and Oberon at Uranus and Triton and Nereid at Neptune). In addition, Pluto has a relatively large Moon (Charon) which is about half its size. Whereas the surfaces of the Moons of Uranus and Neptune are weathered principally by the magnetospheric plasmas [72], the surface of Charon is exposed only to the solar wind and cosmic rays. This is also the case for Pluto's surface when it is far from the Sun on its eccentric orbit and the atmosphere freezes out [73]. Pluto and Triton are thought to be related to the Kuiper belt objects discussed earlier and have methane and nitrogen atmospheres over an icy subsurface.

Uranus is unique in that its axis is tipped $\sim 90°$ to the ecliptic plane, due presumably to a collision with a large object; there is a large angle between the magnetic and rotation axis, so the plasma trapping is not efficient. Therefore, the main plasma component is probably energetic protons from hydrogen in the atmosphere of Uranus, or the penetrating solar wind. It appears that the surfaces are radiation-weathered dark ice that contain some carbon species, probably CO or CO_2 [65]. It also has an unusual ring composed of dark particles, probably a radiation-carbonized material.

5. Upcoming planetary missions and challenges for surface scientists

5.1. Upcoming missions

There are a number of exciting experiments that will be flown on upcoming NASA space missions, and these will present challenging opportunities to the surface science community. We describe a few of these below.

5.1.1. Capturing the Sun: the Genesis Discovery mission [74]

The Genesis mission has an ambitious goal, to collect and return solar matter for analysis in terrestrial laboratories. Collection and analysis of the solar wind ions will provide unprecedented insights into the composition of the original solar nebula, the matter that condensed to form our solar system. Scheduled to be launched in late 2000, the Genesis spacecraft is built around a sample return canister that houses collector arrays. These arrays are high purity materials that will be exposed to the solar wind and will collect ions by implantation. The arrays will be located a million miles from Earth at a point in space that every first-year physics student has computed, where Earth and Sun's gravity balance each other. After two years, the collector arrays will be restored in the contamination-tight canister and returned to Earth for recovery and testing.

Analysis of the precious samples will focus on establishing the isotopic and elemental abundances of the solar wind. A number of sensitive and accurate analytical methods are expected to be applied, including resonance ionization mass spectrometry (RIMS). RIMS is a surface analytical method that has a unique combination of capabilities no other single analytical instrument can match, i.e., unambiguous identification of elemental impurities in the surface regions of solids at trace levels with single monolayer resolution [75]. The capabilities of RIMS are well matched to the needs of the Genesis mission, where solar wind constituents will be implanted at levels down to 0.1 ppt (parts per trillion) at depths $\leqslant$ 100 nm. The specific RIMS instrument proposed for this work is referred to as SARISA (surface analysis by resonance ionization of sputtered atoms), and it employs resonantly-enhanced multi-photon ionization (REMPI) to optimize selectivity and sensitivity [76] in the detection of trace atoms sputtered from the target. REMPI can photoionize ground state atoms with an efficiency near 100%, so that a substantial fraction of the sputtered atoms can be detected. This is indeed an ideal tool for these important studies!

5.1.2. Exploring Saturn: the CASSINI mission

Cassini is likely to be the last of the large spacecraft sent to the outer solar system in the foreseeable future. Cassini will launch a probe into the atmosphere of Titan, the large Moon of Saturn which has an atmosphere thicker than that of Earth. Like the Galileo spacecraft, which is now completing its study of the Jovian system, the Cassini orbiter has a full complement of instruments to study Saturn and Titan, including a UV spectrometer, the ability to image through a number of optical filters, and the visual and infrared mapping spectrometer, the equivalent of Galileo's NIMS discussed above but with a somewhat larger spectral range [73]. In addition, there is a full complement of instruments to measure the plasma and magnetic fields and to detect "dust" impacts. The surface studies, therefore, are done remotely in orbit.

Although a principal goal of the Cassini mission is to understand the atmospheres of Saturn and Titan, another main goal is to understand the origins and evolution of the icy satellites and ring particles that are imbedded in the hot plasma trapped in Saturn's magnetosphere. Again surface physics is a dominant concern since the trapped plasma is self-sustained by sputtering and decomposition of the surface materials [4]. Because the icy Moons of Saturn are smaller than the Galilean satellites, there is no gravity filter and most of the sputtered material escapes directly from the satellites and orbits as an ambient neutral gas within Saturn's magnetosphere. Quite remarkably the OH component of this toroidal neutral atmosphere has already been imaged [70].

Since the neutrals ejected from the surface are eventually ionized by the electrons in the plasma, the plasma-ion composition is a *direct measure of the satellite's surface composition* [3]. This is an exciting prospect for surface scientists. That is, measuring the accumulated plasma is equivalent to performing a post-ionization SIMS study of the surfaces of the Moons and ring particles. Since it is also well known to the surface science community that, although the most volatile species are removed first by sputtering, after long-term bombardment the ejected material is a reflection of the *bulk* composition [77]. Therefore, whereas the spectral instrument only give a description of the surface layer depleted in the most volatile species, plasma mass spectrometry can indicate the subsurface materials in the absence of rapid re-coating.

Because of the above, a critical instrument for surface science at Saturn is CAPS (the Cassini Plasma Science Instrument [78]). This is the first time-of-flight mass spectrometer sent to the outer solar system. Whereas the Galileo plasma science studies were not able to give reasonable mass analysis of the low energy plasma and no information on molecular ions, CAPS will determine both the atomic and molecular composition of the low energy (<40 keV) component of the sputter-produced plasma. Cassini will also have detectors to measure the flux and masses of the very energetic ions (e.g., Fig. 3 for Galileo), but these highly accelerated ions will mostly be atomic. Though an indication of the atomic composition, these ions will also have experienced considerable transport during the acceleration process, so that the source region is not as easily identified. CAPS also can distinguish freshly formed ions from equilibrated ions based on the energy spectra of the ions. Therefore, the ability of CAPS to measure the molecular composition of the ions freshly formed from the sputter ejecta, combined with the spectral mapping of the satellite surfaces, will allow planetary scientists working with surface scientists to determine the composition of Saturn's Moons and ring particles. This is an exciting and challenging prospect which begins in 2004 when Cassini arrives at Saturn.

5.1.3. Europa Orbiter

Europa is of one of the highest priority targets for an outer solar system exploration mission. If subsurface liquid water or even warm subsurface ice were to exist on Europa, there is the possibility of prebiotic processes or even the possibility of life, perhaps forming near undersea volcanic vents. As a first step the Europa Orbiter is proposed to determine the presence or absence of a subsurface ocean, to characterize the three dimensional distribution of any subsurface liquid water and its overlying ice layers, and to understand the formation of surface features (e.g., Fig. 10), including sites of recent or current activity. Although the final payload has not been decided this will include instruments for precise determination of gravitational field, laser altimetry, ice-penetrating radar, and, more relevant to our discussions, imaging using either filters or a spectrometer and, possibly, a mass spectrometer. The proposed schedule is: following launch in 2003, Europa Orbiter will arrive at Jupiter's system in 2007 and enter orbit around Europa in 2009.

5.1.4. Pluto/Kuiper express

Pluto, the smallest planet, has remained enigmatic since its discovery in 1930 and is the only planet in our solar system not yet viewed close-up by spacecraft. Given its distance and size, it is a challenge for planetary astronomers. Although there has been recent progress in determining the atmosphere and surface composition, many of the key questions about Pluto and its satellite Charon await the close-up observation of a space flight mission, the Pluto/Kuiper Express [71]. The goals of the mission are to characterize surface geology and morphology and map the surface composition of Pluto and Charon, and to characterize the neutral atmosphere of Pluto and its escape rate. A possible extension is to fly by one or more Kuiper Disk objects. The strawman payload contains imaging/mapping spectrometers in the visible and IR, and a UV spectrometer. The study of the morphology of these objects will use the radio link to earth and be based on orbit analysis and occultations of the spacecraft. Although it is called a planet, Pluto may have been a member of the Kuiper Belt of icy objects mentioned above. It also is thought to be similar in many ways to Triton, the large moon of Neptune which is already known to have an active surface. On both objects and on the Kuiper Belt objects the surface properties are thought to be affected by the incident radiation as discussed. The launch is planned for around 2010 or soon after with the arrival 8–12 years later.

5.2. Challenges to surface scientists in model studies

5.2.1. Materials

To enhance their impact and credibility in the planetary sciences community, surface scientists will need to move away from crystalline surfaces of elemental solids and binary oxides and study more complex materials characteristic of the solar system. Many interesting crystalline materials exist that are good models for the Moon's surface, e.g., surfaces of feldspars ($NaAlSi_3O_3$, $KAlSi_3O_8$), or olivine, or plagioclase. Iron silicates are ubiquitous in meteorites and (presumably) asteroids. Due to space weathering, amorphous non-stoichiometric surfaces are ever present on the airless bodies of the solar system. Ices of condensed gases are a fertile areas as models of icy satellites and planets, particularly mixtures of gases and briny solutions. Whereas the thermal and non-thermal chemistry of water ice surfaces have been extremely well studied via TPD, ESD, PSD, etc., there is little or nothing known about ESD/PSD of frozen salt solutions or hydrated salt minerals. Porous materials—low temperature ices as well as powdered solids—present new challenges.

5.2.2. Beam damage and space weathering

The effects of all forms of radiation on the space weathering of asteroid-like surfaces need to be examined. Ion, electron and even laser beams (to simulate melting that occurs in micrometeorite impact) can be used to bombard mineral surfaces. What are the structural/chemical/electronic changes that lead to alterations in optical properties?

5.2.3. Role of ion sputtering and DIET

It appears to be clear that PSD can contribute to the lunar Na atmosphere and that DIET leads to the production of atomic and molecular oxygen at/near Europa and Ganymede, but the detailed role of DIET processes (ESD and PSD) in desorption from more complex surfaces is not known. Thresholds, absolute cross-sections and yields, and velocity distributions of products are all necessary information for planetary modelers. Cross-sections and sputtering yields for ion/solid collisions are generally not available for many magnetosphere ions colliding with complex planetary surfaces. The possible effects of DIET and sputtering on unusual surface isotopic abundances, and the huge disparity between surface composition and atmospheric abundances (in tenuous atmospheres) require further investigation. Ion-induced chemical reactions (e.g., formation of volatile H-containing molecules due to bombardment of surfaces by protons in the solar wind) are virtually unexplored. Theoretical calculations of thresholds, cross-sections and desorption yields are non-existent.

5.2.4. Model calculations

Because experiments cannot be carried out for the full range of ion and electron energies and ion types indicated in Figs. 2, 3 and Table 1, model descriptions of the radiolysis and DIET processes are absolutely essential. The model calculations that are required range from simple analytical analysis of laboratory data to detailed calculations of the effects of the interaction of radiation on surfaces in a vacuum. For ion–solid collisions, the energy deposition and initial transport are reasonably well in hand, and considerable progress has been made in calculating desorption of adsorbed species for many special cases; however, there are huge gaps in our understanding that do not allow us to extrapolate ideas learned to new materials or to other radiation types and other energy regimes. In addition, many of the simple models used for sputtering, such as the collision cascade and thermal spike models, either fail totally or are inapplicable to the processes described above. Therefore, in many instances, detailed classical or quantum molecular dynamics (MD) calculations may be required. For instance, thermal spike models of sputtering from a cylindrically energized region about an ion track appeared to well fit and allow extrapolation of the data on the electronic sputtering of ices by fast ions [79]. However, recent MD calculations have shown that apparent agreement to be completely fortuitous [80] at the high excitation densities of interest.

Moreover, lack of understanding exists at a more fundamental level. At present, although the database for electronic sputtering of ices by energetic ions is relatively large [4,81], a detailed understanding of the radiative and non-radiative decay processes leading to desorption exists only for the rare-gas solids. The electronic processes in molecular solids are only understood phenomenologically, as indicated in some of the discussion above. This is not surprising as these processes are strongly affected by local temperature, structure and composition, and by the complex chemistry induced in the surfaces and within the solids. However, although the description of such processes can be difficult, the motivation for understanding these processes is rather high. That is, a detailed understanding of the relevant surface processes can lead to an understanding of the origins and evolution of interesting objects in our solar system and, possibly, the origins of potential biological process on objects other than the Earth.

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