Space weathering on airless bodies

Carle M. Pieters¹ and Sarah K. Noble²

¹Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, Rhode Island, USA, ²Planetary Science Division, NASA Headquarters, Washington, District of Columbia, USA

Abstract Space weathering refers to alteration that occurs in the space environment with time. Lunar samples, and to some extent meteorites, have provided a benchmark for understanding the processes and products of space weathering. Lunar soils are derived principally from local materials but have accumulated a range of optically active opaque particles (OAOpq) that include nanophase metallic iron on/in rims formed on individual grains (impacting a red slope to visible and near-infrared reflectance) and larger iron particles (which darken across all wavelengths) such as are often found within the interior of recycled grains. Space weathering of other anhydrous silicate bodies, such as Mercury and some asteroids, produces different forms and relative abundance of OAOpq particles depending on the particular environment. If the development of OAOpq particles is minimized (such as at Vesta), contamination by exogenic material and regolith mixing become the dominant space weathering processes. Volatile-rich bodies and those composed of abundant hydrous minerals (dwarf planet Ceres, many dark asteroids, and outer solar system satellites) are affected by space weathering processes differently than the silicate bodies of the inner solar system. However, the space weathering products of these bodies are currently poorly understood and the physics and chemistry of space weathering in different environments are areas of active research.

1. Introduction

Materials exposed to the harsh space environment are gradually altered in both physical and compositional properties to some degree. The generic definition of space weathering refers to this process. Simply stated, space weathering is the gradual alteration of materials when they are exposed to a variety of natural processes that occur in the space environment. Understanding the causes and the effects of space weathering on different planetary surfaces, however, is not simple. There are multiple simultaneous processes that can and do alter surface materials on bodies that are not protected by an atmosphere. Related concepts found throughout the literature are soil maturity and exposure age. Soil maturity is a relative term, commonly used for the Moon, that is intended to evaluate the degree to which a given surface soil has accumulated space weathering products [e.g., Morris, 1978; Lucey et al., 2000]. On the other hand, exposure age is a quantitative laboratory measure of how long a rock or soil grain has been exposed to space and is based on precise measurements of accumulated products such as solar wind noble gases or cosmic ray tracks [e.g., Zinner, 1980; Berger and Keller, 2015a]. The discussion presented here focuses on space weathering processes and their alteration products as currently observed for airless bodies of the solar system.

Space weathering processes can be loosely grouped in two broad categories related to (i) random impacts by small particles or debris found throughout the solar system or (ii) irradiation by electromagnetic radiation or atomic particles from the Sun, galactic sources, or magnetosphere. The wide range of impact and irradiation subcategories span numerous specific processes, many of which can be evaluated more directly with observations, experiments, and/or modeling. The energy released in impacts, for example, breaks apart larger particles into smaller particles (comminution), but it also melts and vaporizes some of the host and impactor material (which leads to a range of possible alteration products). Depending on impact parameters (velocity, target composition, geometry, etc.), a portion of the impactor may be retained and mixed with the host in the combined product. Repeated impacts of various sizes also stir and mix previously processed regolith particles to different depths (known as gardening a soil), so the actual time spent on the surface by an individual grain varies stochastically. At the atomic or molecular scale, individual grains residing on the surface are awash in energetic solar wind atoms or ions leading to a release and/or rearrangement of surface components by sputtering. The original crystalline structure of the uppermost surface of a grain can record and be damaged by intense solar UV radiation and energetic cosmic rays. Diurnal thermal cycling occurs from solar insolation during rotation (rapid or slow) of the planetary body. This not only can lead to structural fatigue of surface
materials but may also alter composition through loss of volatile species by radiant heating or sublimation. With time, a host of alteration products accumulate on the surface and are recycled multiple times through several of the processes mentioned above and illustrated in Figure 1.

Due to the diversity of environments and type of materials comprising planetary surfaces, space weathering can have many forms and is inherently controlled by which processes are most active in a specific situation. Combined products of space weathering processes are necessarily a function of location in the solar system (impact speed and flux, radiation environment, and temperature), type of planetary surface (composition, size, and texture of the host), and length of time a surface is exposed. Experience from the Moon and virtually all planetary bodies visited to date indicates that ancient surfaces consist of coarse to fine particulate material. Boulders and outcrops of rocky or coherent solid material are common, but a particulate regolith develops with time. From our current experience, it is largely the regolith that accumulates and records the principal effects of space weathering.

As highlighted below, currently the regolith of two extraterrestrial bodies has been directly sampled (the Moon and the near-Earth asteroid Itokawa), and both of these bodies have evolved near 1 AU. These samples and the ongoing detailed analyses in Earth-based laboratories provide a cornerstone for recognizing and understanding key aspects of several space weathering effects. Using the insights gained from these samples, it is often possible to extrapolate understanding of weathering processes to bodies for which we have only remote data. A handful of additional bodies have been visited by spacecraft and studied in detail for extended periods with orbiting remote sensors (Mercury, Eros, Vesta, and recently dwarf planet Ceres and comet Churyumov-Gerasimenko). The satellites of Mars, Jupiter, and Saturn have been studied to lesser degrees through the decades by multiple flybys of instrumented spacecraft. Seven additional asteroids have been observed with instruments during a single flyby of a spacecraft (usually on its way elsewhere for its prime mission). Most recently, the most distant solar system objects visited, Pluto and its satellites, have revealed some of their secrets. The amount and type of data now available to study the surfaces of airless bodies is exceptional—but it is also extremely uneven in character and quality. Summarized in the following sections are the various forms of space weathering that are now recognized (or hypothesized) based on the clues currently available from the data in hand.

A few scientific debates have arisen about processes and products of space weathering, largely due to the inherent complexity of the natural environment. One of the earliest issues centered on interpretation of observed properties of a large class of asteroids, the so called “S-type” asteroids [Bell et al., 1989; Chapman, 1996, 2004]. On the one hand, principal minerals identified on the surfaces of these asteroids from near-infrared telescopic reflectance spectra were found to be low-Ca pyroxene and olivine, suggesting that these asteroids are comparable to the most common type of meteorite that falls to Earth, the ordinary chondrites. However, in detail the optical properties of the S-type asteroids and the ordinary chondrites differ in an important manner: the asteroids exhibit an overall red-sloped continuum that varies among asteroids whereas the chondrites do not. One interpretation suggested that this difference was simply due to space weathering on the asteroid’s surface. An alternate interpretation was that the S-type asteroids experienced an inherently different evolution than the relatively primitive ordinary chondrites, and the distinctive optical
properties of the asteroids arise from a pervasive presence of exposed iron metal that resulted from a major melting and differentiation event early in the asteroid’s evolution. As discussed in the sections below, the debate over this “S-type Conundrum” was largely resolved (in favor of the space weathering interpretation). This closure became possible when (1) surface processes that produce a red-sloped continuum became understood from lunar sample analyses and experiments and (2) S-type asteroids (Gaspra, Ida, Eros, and Itakowa) were visited by spacecraft, with samples returned to Earth for analyses from one (Itakowa) by the Hayabusa spacecraft.

The concept that space weathering produces a measurable effect on the surface properties of many/most airless bodies became well established with analyses of lunar samples, but understanding the physics and products of interwoven processes that are involved encompasses multiple areas of active research. For example, even at 1 AU where the Moon and near-Earth asteroids reside, discussion and experimental approaches focus on the relative effects of products from micrometeorite impacts versus those arising from solar wind interactions. Imbedded within this debate is the timescale for either process to accumulate measurable products within a continually mixed regolith. The unique advantage of being able to analyze actual lunar and asteroid regolith samples using ever increasingly sophisticated instruments in Earth-based laboratories cannot be overstated. Likewise, understanding the effects of weathering processes naturally becomes even more difficult and complex for other environments of the solar system that are less well known.

2. Lunar Space Weathering

The history of our understanding of weathering effects on the Moon is well described in a review paper by Hapke [2001], starting with the classic Gold [1955] observation that lunar crater rays disappear over time. But it was the return of lunar soils more than 45 years ago that changed forever our understanding of the characteristics of the regolith on airless bodies and forced us to reexamine how we use optical tools to evaluate composition remotely. When Apollo soils were evaluated in Earth-based laboratories, it was quickly found that their optical properties differ greatly from those of pulverized rocks from the same site [Adams and McCord, 1970]. Natural lunar soils are darker (especially at visible wavelengths), and absorptions that are diagnostic of minerals present are considerably weaker. As illustrated in Figure 2, these same properties are found in remote measurements that compare background soil with materials freshly exposed at a young crater. The observations were irrefutable: fresh lunar materials exposed on the surface are systematically altered with time. Identifying the cause of the alteration was more difficult. Most of the early literature focused on measuring the presence of dark amorphous “glass” or “agglutinates” (the complex, dark glass-welded aggregates found in lunar soils). Unfortunately, these initial inquiries simply identified lunar products of exposure to the space environment but did not (and could not at that time) address the complexity of
these unusual materials and the physical/chemical origin for the observed optical effects of agglutinates and natural lunar soils. That came much later as the pieces gradually came together and data accumulated from multiple directions [e.g., Pieters et al., 2000; Hapke, 2001; Noble et al., 2007; Domingue et al., 2014].

Cassidy and Hapke [1975] were the first to suggest that the actual culprit responsible for these optical changes on the Moon could be tiny particles of metallic iron, alternately referred to in the literature as “nanophase iron” (npFeO) or “submicroscopic iron.” The groundbreaking transmission electron microscope (TEM) studies of Keller and McKay [1993, 1997] finally resolved these particles and revealed their distribution in lunar soils. There are two distinct populations of these opaque iron grains in lunar soils: they are found distributed throughout agglutinates and in depositional (“inclusion-rich”) rims on individual grains such as illustrated in Figure 3a. In addition to the abundant deposited rims, Keller and McKay [1993, 1997] also identified solar wind damaged “amorphous rims,” which contain little or no npFeO and are compositionally linked to the host grain as illustrated in Figure 3b. In some cases there are “multiple” rims in which an amorphous rim is overlain by a depositional rim.

The npFeO found in the depositional rims is very small, with a range of ~1–10 nm in diameter and an average of ~3 nm [Keller and Clemett, 2001], while the iron particles in agglutinates come in a much wider range of sizes, up to hundreds of nanometers in diameter. Size is important because the optical changes that are attributed to space weathering are highly dependent on the size and quantity of nanophase opaques. Britt and Pieters [1994] found that finely dispersed larger (micron-scale) particles of nickel iron and FeS cause a reduction in reflectance throughout the visible/near-infrared with no apparent effect on continuum slope. It was suggested by Keller et al. [1998] that very small npFeO particles (<5 nm) cause spectral reddening, whereas larger particles introduce darkening without reddening. Noble et al. [2007] explored the effects of size and concentration of nanophase iron by systematically impregnating a series of silica gels with different pore sizes with npFeO (Figure 4). Results quantified the earlier observations and demonstrated that small iron particles (<40 nm) cause systematic reddening and darkening across the visible/near-infrared, and larger iron particles (>40 nm) cause darkening, but not reddening, throughout the wavelength range. Lucey and Noble [2008] expanded on the Noble et al. [2007] study by using methods developed by Hapke [1981, 1993, 2001] based on Rayleigh scattering to compute model spectra for comparison to the Noble et al. [2007] experiments. The results successfully modeled the experiments that contained small npFeO of sizes up to about 40–50 nm; however, there were significant deviations between model and experiment for samples with abundant larger particles (>40–50 nm). The failure of the model spectra to match these spectra for larger iron particles occurs because these particles do not behave as highly efficient Rayleigh absorbers (as assumed in Hapke’s [2001] model) and so cannot be modeled simply by Rayleigh scattering. A more successful modeling result is found when a Mie scattering component is added to account for the larger particles [Lucey and Riner, 2011]. This size cutoff is close to the limit of detectability of ferromagnetic resonance for iron particles (~35 nm) [Morris, 1976]; thus, the standard measure of lunar soil maturity, I/FeO, is a measure of just the npFeO contribution and does not help quantify the larger particles (though for the Moon the two components are generally well correlated).

A detailed coordinated study of a representative suite of lunar soils from all Apollo sites was undertaken to document the petrographic, chemical, and optical properties as well as I/FeO values for lunar soils across a range of soil maturity. Referred to as the Lunar Soil Characterization Consortium, this effort produced integrated detailed data for properties relevant to space weathering [Taylor et al., 2001, 2010]. The data document that for any given soil, values of I/FeO increase with decreasing particle size and that npFeO thus principally resides on the surface of particles.

The combination of sample observations [Keller and McKay, 1993, 1997; Taylor et al., 2001, 2010], experimental results [Noble et al., 2007], and modeling [Lucey and Noble, 2008; Lucey and Riner, 2011] demonstrates that nanophase iron-bearing rims and agglutinates both contribute important optical effects but result from distinctly different combinations of space weathering processes. The small npFeO in rims causes reddening, while the abundant large metal particles in agglutinates result in darkening. We have adopted the terminology “nanophase metallic iron” (npFeO) or, more generally, “nanophase opaques” (npOpaq) for these very small particles that reddened a spectrum and “Britt-Pieters” (B-P) particles (as suggested in Lucey and Noble [2008] and Lucey and Riner [2011]) for the somewhat larger particles that darken without reddening. We propose the term “optically active” opaque particles (OAOpq) to encompass both size ranges.
Figure 3. (a) TEM image of a lunar agglutinate illustrating the presence of npFe$_0$ forming two layers within the rim but larger Fe$_0$ in the interior. (b) TEM bright field images and chemical maps of typical lunar soil rims. The plagioclase grain (top) has a depositional npFe-rich rim, which is chemically distinct from the host grain. The cristobalite grain (bottom) has an amorphous solar wind damage rim compositionally indistinguishable from the host grain (Images courtesy: Lindsay Keller).
3. The Debate Over Irradiation and Impact Melt/Vapor Deposition
3.1. Lunar Sample and Meteorite Laboratory Studies

The formation mechanisms for the optically active iron in lunar rims and agglutinates have long been debated. Many workers have tried to simulate space weathering in the laboratory by various means. The first such experiments [e.g., Wehner, 1961; Hapke, 1966] irradiated solid surfaces with H ions to reproduce the effects of solar wind; however, no reddening or darkening was observed. The key, it turned out, was powdered surfaces, and when these were irradiated [e.g., Wehner, 1964; Hapke, 1973] the samples did in fact show substantial reddening and darkening, correlated to the amount of Fe present. These results appeared to suggest that solar wind was a main driver of space weathering. But what role do micrometeoroids play? Moroz et al. [1996] were the first to use lasers to simulate the effects of micrometeorite bombardment, but the long laser pulse duration (0.5–1 μs) was unrealistic for typical micrometeorite impacts, and although the samples did show reddening and darkening, it was thought to be largely due to the rapid melting and recrystallization of the materials. Several researchers [e.g., Yamada et al., 1999; Sasaki et al., 2001, 2003; Brunetto et al., 2006; Gillis-Davis and Scott, 2014; Gillis-Davis et al., 2015] have successfully used nanosecond pulse lasers, which better reproduce the heating profile, though not the shock, of a micrometeorite impact. TEM analyses of these laser-irradiated analog products show that indeed this process produces optically active iron particles. Figure 5 compares an experimentally laser-irradiated olivine with a natural micrometeorite impact into an olivine grain in a lunar rock. The laser-irradiated olivine in Figure 5 (left) received a single laser shot [Noble et al., 2011]. The npFe⁰ produced is roughly the same size as is seen in natural impacts [Noble et al., 2016] and in rims on soil grains. Many laser analog experiments, however, raster the laser over the surface several times, melting and remelting that surface layer. This seems to also result in the creation of larger iron particles [Sasaki et al., 2001, 2003; Kurahashi et al., 2002; Rout et al., 2008]. These results are consistent with our understanding of the formation mechanism for the larger B-P particles in agglutinates, because as the small npFe⁰ in rims is melted and incorporated into agglutinitic glass there is an opportunity for the small iron to coalesce into larger particles.

Another approach is to evaluate the character of rims developed on individual grains with the actual exposure age. By counting the accumulation of solar flare particle tracks, it is now possible to determine the cumulative exposure age of an individual soil grain [Berger and Keller, 2015a]. Zhang and Keller [2011] and Keller and Zhang [2015] looked at the thickness of amorphous radiation-damage rims and depositional rims compared to the solar track density. The rim thickness for the radiation-damage rims increases with exposure age as damage accumulates; the depositional rims, in contrast, show no correlation with time. This indicates that creation of the depositional rims is a completely stochastic process, and formation of these rims typically happens in a single event, as deposition of vapor and/or melt in an impact, rather than a slow buildup via sputtering. Thus, retaining and recycling grains during regolith gardening are important constraints on soil evolution. Both types of rims are roughly equally common in a well-developed mature soil [Keller and McKay, 1997]. Both seem to accumulate ~10⁶–10⁷ years of integrated exposure in mature lunar soils based on the solar flare track densities in individual space-weathered grains [Keller and Zhang, 2015].
It is clear from the Zhang and Keller [2011] integrated study of natural lunar soil grains that the npFe\(^0\) found in lunar soil rims is created largely through impact processes rather than solar wind processes. However, although most experiments mimicking micrometeorite impacts produce npFe\(^0\) apparently without the presence of H, it remains unclear if solar wind implantation of H is a necessary precursor to allow for the reduction of iron on the lunar surface.

3.2. Lunar Swirls

It was initially hoped that the special environment found at unusual sinuous albedo features on the Moon, referred to as lunar “swirls,” would provide insight into the character of lunar space weathering. These bright mysterious features contain no topographic relief, and all are associated with local magnetic anomalies (although not all magnetic anomalies found on the Moon are associated with detectible swirls) [Blewett et al., 2011; Denevi et al., 2016]. It was commonly hypothesized that the local brightness at swirls was due to protection of the surface from the solar wind by the local magnetic field, resulting in reduced space weathering at these features [e.g., Hood and Schubert, 1980; Hood and Williams, 1989]. Indeed, measurements of swirls with modern sensors detect a deflection of solar wind particles associated with the swirl [Kurata et al., 2005; Wieser et al., 2010; Lue et al., 2011]. Similarly, abundance of the pervasive surficial OH recently detected across the Moon, which is believed to be formed from solar wind H interacting with O-rich surface silicates [Pieters et al., 2009; Sunshine et al., 2009; McCord et al., 2011], is found to be lower in the bright portion of lunar swirls [Kramer et al., 2011; Pieters and Garrick-Bethell, 2015], confirming a reduced presence of (solar wind) H at swirls.

Although the local magnetic field at lunar swirls thus appears to protect the surface from exposure to much of solar wind H, modern spectroscopic near-infrared measurements demonstrate that the surface of swirls is not consistent with immature regolith [Pieters et al., 2014a]. This significant spectroscopic distinction between normal space weathering trends across fresh craters and that found across lunar swirls is illustrated in Figure 6. The M\(^3\) images cover a flat mare region to the southwest of the main Reiner Gamma swirl. The area contains several small fresh craters, numerous bright and dark markings of swirls, and background mare soil. The bright immature soils associated with small fresh craters are readily recognized in the top image as small localized generally circular bright areas at M\(^3\) visible wavelength. These are easily distinguished from the bright sinuous and diffuse markings of the swirls. However, for the lower near-infrared image at 2200 nm (near the center of a diagnostic pyroxene absorption as illustrated in Figure 2), the immature mare craters largely disappear, but the bright swirls are not affected.

Comparison of the typical maturity trend across a fresh mare crater and surrounding mature soil (Figure 2, right) with the traverse across a bright swirl into a neighboring dark lane (Figure 6, right) illustrates that...
the two environments produce entirely different optical effects. In contrast to the prominent pyroxene ferrous absorptions associated with relatively high albedo fresh mare material, the bright swirls exhibit very little difference in absorption band strength compared with dark lanes and nearby mature soils in mare regions, but there is a prominent overall increase in albedo across all wavelengths. Although the low OH found at bright regions of mare swirls indicate that they are less affected by solar wind H than typical mare soils, their mineralogy has clearly been altered (weak pyroxene absorptions), and the bulk properties of swirls are certainly not comparable to normal immature lunar materials (Figure 2).

These unusual albedo features and their environment remain shrouded in mystery. It is unknown whether the magnetic environment is sufficiently strong to also deflect heavier energetic particles, and the cause of the general wavelength-independent brightening of the swirl has not been determined. For example, in addition to hypotheses of different soil products formed at swirls due to lower solar wind interactions [e.g., Hemingway et al., 2015], other hypotheses include particle size sorting in a charged-magnetic environment, magnetic sorting of npFe\textsuperscript{0}-bearing and B-P particles during regolith gardening, development of differential rim populations of soil grains, and regolith scouring during cometary interaction [Garrick-Bethell et al., 2011; Pieters et al., 2014a; Keller and Zhang, 2015; Syal and Schultz, 2015]. In summary, although clearly associated with local magnetic anomalies (minimagnetospheres), swirls exhibit their own distinctive optical trends, the cause of which has yet to be determined. They remain some of the most lovely and mysterious features on the lunar surface and certainly merit closer examination in situ.

4. Space Weathering on Mercury

The environment and composition of Mercury is substantially different from that found on the Moon, and those differences influence how space weathering manifests in the Mercurian regolith. The speed and flux of impactors is substantially greater at Mercury because of its proximity to the Sun and greater mass [Cintala, 1992; Marchi et al., 2009]. Per unit area, impacts on Mercury are predicted to produce 13.5 times the melt and 19.5 times the vapor than is produced by similar impacts on the Moon [Cintala, 1992]. Other space weathering processes such as irradiation are also approximately an order of magnitude stronger on Mercury compared with the Moon [Domingue et al., 2014]. Based on Mercury’s reflectance spectrum, which lacks diagnostic ferrous absorptions (Figure 7), it has long been assumed that Mercury’s surface is poor in ferrous iron [McCord and Clark, 1979]. Recent results from MERCURY Surface, SPACE ENVIRONMENT, GEOchemistry,
and Ranging (MESSENGER) have confirmed this and provide additional compositional information about the planet indicating substantially less than 4 wt % Fe across the surface [e.g., Nittler et al., 2011; Evans et al., 2012; Wieder et al., 2014]. Furthermore, the composition of the surface was found to be sulfur rich, with more sulfur than iron. Mercury’s regolith is also exposed to an extreme temperature regime. This combination of new compositional information and distinct optical properties associated with fresh craters clearly defines the type of space weathering on Mercury seen in Figure 7. Although no ferrous absorptions are present, fresh material exhibits a higher albedo and less steep continuum slope [Robinson et al., 2008; McClintock et al., 2008; Blewett et al., 2009; Izenberg et al., 2014; Domingue et al., 2014; Murchie et al., 2015].

Before the arrival of MESSENGER, Noble and Pieters [2003] predicted that due to the higher flux, greater speeds, and higher temperatures, space weathering products would be created at an accelerated rate on Mercury compared to the Moon. Agglutinates make up a substantial fraction of mature lunar soils (up to 60%); a mature soil on Mercury probably has little original crystalline material remaining. Although there is less iron available, this extreme environment should result in the creation of larger iron/opaque particles as the repeated melting allows small particles to merge with others and coalesce [Noble et al., 2007].

Lucey and Riner [2011] modeled a MESSENGER spectrum, accounting separately for the effects of nanophase and Britt-Pieters particles. Compared to the lunar case, they found that the MESSENGER spectrum requires more nanophase as well as Britt-Pieters (opaque) particles, consistent with the higher melt and vapor predicted from micrometeorites [Cintala, 1992]. Unlike the Moon, where only a small percentage of the available iron (largely FeO) is reduced by space weathering, on Mercury it appears that all, or nearly all, of the endogenic and exogenic available iron is processed. Furthermore, the models of Lucey and Riner [2011] suggest that the ratio of larger Britt-Pieters particles to smaller nanophase particles is significantly higher compared to the lunar case (~6 compared to ~2 for the Moon), consistent with the predictions of Noble and Pieters [2003] and Noble et al. [2007].

Even after accounting for both size ranges of optically active iron, modeling suggests that there may be other opaques contributing to the space weathering continuum of Mercury’s spectrum, such as nanophase amorphous carbon [Trang et al., 2015]. Impact experiments have demonstrated that carbon-bearing compounds can produce Mercury-like products [Syal et al., 2015], and, indeed, carbon (graphite) is seriously discussed as an ancient crustal component [Vander Kaaden and McCubbin, 2015; Peplowski et al., 2016]. Given the

Figure 7. Comparison of spectra for units of Mercury obtained by Mercury Atmospheric and Surface Composition Spectrometer (MASCS) on MESSENGER [Domingue et al., 2014; Izenberg et al., 2014]. The vertical scale for the young units is almost 2 times that of the older units. Although major mineral/amorphous components of the surface are poorly understood, the optical relation between young and older units directly mimics that seen experimentally with a combination of nanophase and Britt-Pieters opaque particles [e.g., Noble et al., 2007].
relatively high abundance of surface sulfur discovered by MESSENGER [Nittler et al., 2011; Evans et al., 2012], another likely widespread contributor to npOpq and B-P particles on Mercury is a sulfur-bearing opaque compound [e.g., Domingue et al., 2014].

The extreme temperature regime at Mercury also appears to play a role on how space weathering manifests. The “hot poles” (equatorial regions at 0° and 180° longitude) experience temperatures up to ~700 K; these regions also appear to be enriched in Britt-Pieters particles. As predicted by Noble and Pieters [2003], the temperatures reached are high enough that the optically active particles can grow through the process of Ostwald ripening [Trang et al., 2015].

Although the optical and elemental data now available for Mercury from MESSENGER have certainly provided a more detailed understanding of the character and diversity of the surface, it is also clearly a complex and very harsh space weathering environment. It will likely be a long time before samples are available from Mercury, but inferences and comparisons with the Moon have provided considerable insight. A comprehensive assessment of the special environment at Mercury is presented in the review by Domingue et al. [2014].

5. Space Weathering on Near-Earth Asteroids

Any airless body at 1 AU encounters the same space environment conditions as is found at the Moon and Earth. Although still substantial, the uncontrolled variables are reduced to the composition, texture, and mass (gravitational environment) of the host body and the duration of exposure and recycling of particles within the regolith.

5.1. Ordinary Chondrite Bodies

Two near-Earth bodies have been orbited with spacecraft: 433 Eros with the NEAR spacecraft [Cheng, 2002] and 25143 Itokawa with the Hayabusa spacecraft [Tsukiyama, 2014]. Both are classified as an S-type asteroid and have been shown to be of ordinary chondrite composition [Trombka et al., 2000; McCoy et al., 2001; Nakamura et al., 2011]. Though similar in composition and elongate shape, they are quite different in scale: Eros has a mean diameter of 16 km, while Itokawa has a mean diameter of just 0.324 km (Figure 8). Both bodies have smooth regions or “ponds” where it appears that fine-grained material has gathered in areas with low geopotential due to several possible mechanisms [Robinson et al., 2001; Cheng et al., 2002; Domingue et al., 2010] (see review by Roberts et al. [2014]). The ponds on Eros are local features, often in crater bottoms. On Itokawa the “ponding” is a global-scale process but mainly concentrated in two areas: the northern polar region and around the southern polar region including the Muses Sea. These smooth terrains cover roughly 20% of the total surface area of Itokawa [Yano et al., 2006]. Close-up images from Hayabusa indicate that the Itokawa ponds consist of mostly gravel-sized (millimeter-centimeter) grains [Yano et al., 2006].

Global spectra mapping of these bodies indicates that space weathering is taking place. On both bodies, fresh bright materials are observed in regions of steep topographic slopes and craters. On Eros there is a strong albedo effect (contrasts up to 40%) but only very minor color differences (4–8% reddening variations) [Clark et al., 2001]. Weathering on Eros seems to follow a different trend than was seen at Gaspra and Ida in the main asteroid belt (see section 6.1 below), where albedo effects are of the same order as spectral reddening and weakening of absorption bands. Although Gaffey [2010] focuses on a potential ambiguity produced by space weathering, Chapman [2004] discussed the possible reasons for this and concluded that it was likely because Eros is a large near-Earth asteroid and therefore exposed to a different space environment. However, weathering trends on Itokawa do not seem to share the extreme albedo effect but rather show small color and albedo trends similar to those seen at Gaspra and Ida [Hiroi et al., 2006]. Thus, it seems that Eros is the odd one and there must be some environmental or compositional factor controlling the weathering process on Eros that we do not yet understand.

Space weathering has largely been considered to be a soil process, but rocks exposed for extended periods will also incur the effects of space weathering. Weathering patinas on lunar rocks have been described [Wentworth et al., 1999; Noble et al., 2012], but in the lunar case, mature outcrops are only small contributors to the spectrum on a remote sensing scale. Results from the Hayabusa spacecraft at the asteroid Itokawa (Figure 9) suggest that while low gravity does not allow for the development of a mature regolith, weathering patinas can, and do, develop on rock surfaces [Ishiguro et al., 2007]. It is the boulder-rich areas on Itokawa that appear the most weathered, with lower albedos and shallower 1 μm bands [Abe et al., 2006]. The rocks of Eros...
also appear to be notably dark and space weathered [Chapman, 2004]. For small bodies, where there is little soil and a substantial fraction of the exposed surface is rocky, rock weathering may be an important process. Although there is no shortage of ordinary chondrite material on Earth, the samples returned from Itokawa were the first opportunity to study true asteroidal regolith samples from a known asteroid in a laboratory. Despite Itokawa's small size and the difficulty of developing a substantial fine-grained regolith, the Hayabusa mission was able to return hundreds of regolith grains from the Muses Sea region [Yano et al., 2006]. Because of the small quantity of available sample, most individual studies have been limited to looking at a handful of grains, making statistical statements difficult. However, space weathering products have been clearly identified on many grains [Noguchi et al., 2011]. The results not only definitively confirm the link between ordinary chondrites (OCs) and S-type asteroids [Nakamura et al., 2011] but also give us insight into space weathering and regolith processes products on small bodies.

At least two kinds of lunar-like weathering products have been identified on Itokawa grains: vapor deposits and solar wind irradiation effects [Noguchi et al., 2011]. However, the vapor-deposited material found on Itokawa grains is thin (5–15 nm) and contains nanophase opaques (npOpq) that contain sulfur, not just iron. Sulfur-free npFe⁰ particles exist deeper inside (up to 60 nm) some of the iron-bearing silicates where Fe²⁺ is reduced in situ, creating npFe⁰ particles in solar wind amorphous rims, a process occasionally seen in lunar soils as well, particularly in olivine [Berger and Keller, 2015b]. Both processes on Itokawa create small nanophase opaques (~2 nm), similar in size to that seen in rims of lunar grains.

Berger and Keller [2015b] found that the two grains they examined had been buried in a relatively fixed orientation at depths of a few millimeters to a few centimeters for ~10⁵–10⁶ years, based on solar flare track gradients. The solar wind damage rims, on the other hand, indicate that late in their history (<10⁵ years), they were brought to the surface, and the continuous nature of those rims suggests that they must have moved to expose all sides. Furthermore, unlike the sharp angles of lunar soil
grains, some of the Itokawa grains have rounded edges, possibly due to abrasion from seismic-induced grain motion [Tsuchiyama et al., 2011]. Taken together, this suggests that there is little deep overturn/gardening on Itokawa, but the grains at the uppermost surface move about frequently.

5.2. Carbonaceous Chondrite (Primitive) Bodies

Analysis of the regolith grains returned from Itokawa by Hayabusa [Noguchi et al., 2011; Nakamura et al., 2011] provided critical information demonstrating that lunar-like optically active nanophase opaques are produced in the environment of an ordinary chondrite parent body. Such space weathering products occur for these S-type asteroids that contain silicates lithologies consisting of mafic minerals (pyroxene and olivine) as well as Fe-Ni metal and FeS. However, another major class of near-Earth asteroids fall into the C-type class, which are dark and without distinguishing diagnostic absorption bands. It is generally thought that these objects have affinities to the carbonaceous chondrite (CC) class of meteorites that fall to Earth, although no direct link has been made. These CC meteorites are very primitive and typically contain carbon compounds, organics, and hydrous minerals. If they are derived from C-type asteroids, then their distinctive composition is completely different from all the anhydrous materials studied from the Moon and OC parent bodies.

A few laser and ion irradiation experiments relevant to space weathering have been performed with CC meteorites [Moroz et al., 2004; Gillis-Davis et al., 2015; Kaluna et al., 2015; Lantz et al., 2015; Matsuoka et al., 2015] to determine whether products are formed that can be interpreted to result from the space weathering context involving micrometeoroid impact or solar wind interaction. The experimental results have provided highly diverse products, however, and no regular pattern has been detected across samples. From the experiments, it appears that the mineralogy itself has often been readily altered and new and/or additional alteration products are formed for CC-like primitive materials that are specific to the starting composition of the particular parent body.

Fortunately, it is expected that two missions, Hayabusa 2 (JAXA) and OSIRIS-REx (NASA), traveling to two different small C-type near-Earth asteroids will be returning samples from the surface of these asteroids to Earth-based laboratories in the not too distant future. We are not going to make predictions about what form of space weathering processes and products might be found, other than these unique asteroid regolith samples are likely to surprise us with something completely new.

6. Space Weathering on Main Belt Asteroids

6.1. Gaspra and Ida

The Galileo flybys of Gaspra and Ida provided the first close-up views of the surface of asteroids. Both are S-type asteroids similar to Eros, and both show evidence of “lunar-style” space weathering, i.e., a reddened continuum slope and weaker absorption bands compared to the spectra of fresh craters [Chapman, 1996]. The changes are more subtle at Gaspra, which corresponds to the relatively fewer large craters compared to Ida and suggests that Gaspra’s surface is younger. Appearing even less weathered is Dactyl, Ida’s tiny moon, which is too small to retain a regolith. Extrapolating the spectral trend from weathered Ida to fresh Ida to Dactyl points toward the spectra of ordinary chondrites (OCs), as illustrated in Figure 10. This trend provided the first direct link between OCs and S-IV asteroids, thus pointing to space weathering as the likely answer to the S-type conundrum.

6.2. Vesta

The spectrum of asteroid Vesta was one of the first measured for an asteroid using Earth-based spectrophotometry [McCord et al., 1970]. Diagnostic absorption features identified the presence of low-Ca pyroxene and showed the asteroid to have a clear affinity to the HED class of differentiated meteorites (Howardite, Eucrite, and Diogenite). This Vesta-HED association was only strengthened as measurements improved [McFadden et al., 1977; Binzel and Xu, 1993; Gaffey, 1997] and was confirmed with the detailed data acquired by the Dawn mission at Vesta [De Sanctis et al., 2012a]. However, unlike the Moon and near-Earth asteroids, the overall surface of Vesta was able to be directly compared to particulate meteorites prepared to small particle sizes [e.g., Hiroi et al., 1994], and no space weathering effects were necessarily required to fit the lab spectra to the remote observations. This was the conundrum that puzzled the community [Chapman, 2004]; namely, how can highly space-weathered bodies like the Moon, Mercury, and some asteroids coexist with a prominent
asteroid that does not exhibit the distinctive “reddening” associated with exposure to the space environment?

The answer became apparent when Vesta was visited by the Dawn spacecraft, and its physical properties and local mineralogy were measured with modern sensors [e.g., Russell et al., 2013]. Like other silicate bodies, Vesta does contain both fresh and degraded craters, with the fresh craters commonly exhibiting rays of material emanating from the crater resulting in deposits on or disruptions to the surrounding environment (Figure 11). Again, like on other bodies, these rays degrade and disappear with time indicating an active space weathering environment. Although the strength of diagnostic ferrous absorption features was found to decrease a little with increasing development of soil with properties comparable to the background, no change of the near-infrared continuum was observed in local spectra [Pieters et al., 2012]. Independent parallel measurements detected small but distinct amounts of H or OH in a spatially coherent pattern across Vesta [Prettyman et al., 2012; De Sanctis et al., 2012b].

The most likely reason Vesta does not exhibit measurable lunar-like npFeO space weathering products is a combination of its physical environment (lower solar flux and less energetic micrometeoroids) and, more importantly for that environment, its total lack of metallic iron or sulfides that can be mobilized to produce npOpq. In contrast, even though Mercury has very low iron content, it is located in an intense micrometeorite and solar
irradiance environment and has high sulfur content to combine with other elements to produce abundant npOpq as well as B-P particles and hence exhibits extensive lunar-like space weathering. Vesta’s neighboring S-type asteroids across the main belt that exhibit modest lunar-like space weathering (although considerably less than the Moon) are presumed to be of an ordinary chondrite-like composition and thus have abundant metallic iron and FeS that can be readily mobilized to produce the npOpq. It is largely Vesta’s unusual differentiated metal-free basaltic composition in the asteroid belt that allows it to retain its more pristine mineral appearance over billions of years’ exposure.

6.3. Ceres

Ceres is the largest and most massive asteroid in the main asteroid belt, and its spherical shape leads it to be classified as a dwarf planet. Ceres’s low density (2.16 g/c) and recently measured gravity harmonics [Park et al., 2016] confirm that it is volatile rich and experienced some amount of physical and chemical differentiation during its early evolution [Russell et al., 2016]. Ceres is thus a transitional body between the rocky bodies of the inner solar system and the ice-rich bodies of the outer solar system. It exhibits a mineralogy not encountered elsewhere and is not represented in the meteorite collection [De Sanctis et al., 2015; Ammannito et al., 2016]. The overall surface is very dark, and color variations across the visible are only a few percent [Nathues et al., 2015]. Spectral ratio images (illustrated in Figure 12) are required to map and evaluate subtle spatial variations of color. A few small locations are distinctly bright, such as the unusual areas in the center of Occator crater [Russell et al., 2016], which have reflectance 5–8 times greater than surrounding material [Li et al., 2016].

Fresh craters on Ceres (and surrounding ray system when they exist) exhibit distinct optical properties, but these features evolve into background material with time. As Dawn data for Ceres are evaluated, it is clear that a different group of space weathering processes dominate the surface of Ceres compared with those for previously studied bodies. This is most likely related to Ceres’s location in the main asteroid belt and (more importantly) to the inherent compositional character and evolution of its surface. The development of lunar-like anhydrous space weathering npOpq products is likely to be unimportant for volatile-rich Ceres, where large impact craters excavate and distribute volatile-rich materials and hydrated minerals from depth. However, water ice is not stable on the surface of Ceres [Fanale and Salvail, 1989] and will be lost with
time, leaving nonvolatile materials behind. These can consist of salts (including carbonates) previously dissolved in aqueous subsurface materials, as well as a variety of endogenic hydrated minerals and exogenic contaminants. The hypothesis being tested with Dawn data [e.g., Pieters et al., 2016] is that the overall dark surface results from a lag deposit developed over billions of years and that the “blue” large young craters and rays contain a component of residual salts deposited on the surface that have not yet been completely mixed into the background regolith. The processes most likely to be actively involved in space weathering on Ceres are summarized in Figure 13.

7. Space Weathering on the Moons of Mars

The two moons of Mars, Phobos and Deimos, are some of the most enigmatic of airless bodies. They have been measured by sensors on Earth-based telescopes as well as on multiple spacecraft sent to the Mars environs. Since most spacecraft are located closer to Mars than the orbit of Phobos, it is the Mars-facing side of Phobos that is most often observed. Although Phobos is better studied than Deimos, data are severely limited in surface coverage, as well as spatial and spectral resolution provided by available sensors. We thus know less about these moons than we do for many of the other small bodies that have been visited by spacecraft. A major unsolved question is whether these small moons ($D_{\text{Phobos}} = 22.2$ km, $D_{\text{Deimos}} = 12.6$ km) are captured asteroids or are directly related to Mars by accretion of Mars debris resulting from a major impact and subsequently space weathered in situ [e.g., Rosenblatt, 2011].

As can be seen in Figure 14, the present surface of Phobos is not homogeneous. The overall bulk properties could be consistent with either a dark primitive “D-type” asteroid or silicate material of the inner solar system that has been highly, perhaps extremely, space weathered (see data summary in Rivkin et al. [2002], Fraeman et al. [2012, 2014], and Pieters et al. [2014b]). With no obvious diagnostic absorption features readily detected in available visible and near-infrared spectra, the principal variation in optical properties of surface material is largely a distinct difference in continuum slope. In visible wavelength images, regions with a steep (“red”) continuum are also darker, but albedo variations appear less distinct in the near-infrared. The optical differences observed across Phobos could be due to either inherent heterogeneities of materials comprising the satellite or to variations of how regolith forms or is altered and distributed across the surface. The large crater, Stickney, with substantial “blue-sloped” material found on its rim is also on the leading edge of Phobos as it orbits Mars. The satellite is only ~6000 km from the surface of Mars, and particles on or near the surface are necessarily affected by the Mars’s gravity well. Large particles disturbed from the surface are predicted to eventually re-accrete on Phobos after spending time in Mars orbit, whereas fine particles are swept away toward Mars [Ramsley and Head, 2013; Zakharev et al., 2014]. The regolith on Phobos, and by extension on Deimos, is therefore highly evolved and may be relatively mobile, but the origin of the regolith and the satellites themselves is not yet clear.

8. Discussion and Integration

Space weathering was first encountered as a mystery to solve: why do soils returned from the Moon look so very different than the rocks from which they were derived? Solution of this mystery took decades of multiple
investigators probing samples with increasingly sophisticated techniques in the laboratory as well as initiating diverse experiments and modeling in order to converge on an understanding of the dominant processes and products involved [e.g., Pieters et al., 2000; Hapke, 2001].

Through the integration of studies associated with the Moon, S-type asteroids, and Mercury, it is now clear that several common forms of space weathering produce small opaque particles that darken the surface and control its optical properties. It is the size and abundance of these accumulated particles that is very important in determining the optical effects. Since our understanding of this opaque component of observed space weathering products has evolved considerably over the last few decades as documented above, we recommend the following terminology to be used when describing opaque or absorbing particles in order to be consistent and avoid confusion:

1. Nanophase metallic iron (npFe$^0$) or other nanophase opaque (npOpq) particles. These are typically in the size range of 1–15 nm and accumulate on/in the rims of individual regolith grains imparting a red-sloped continuum in the visible to near-infrared. At low abundances, these particles affect the shorter wavelengths more strongly resulting in a curved continuum.

2. Britt-Pieters (B-P) opaque particles (Fe$^0$, FeS, etc). These are in the size range from ~40 nm to 2 μm (commonly termed microphase) and are dispersed throughout the matrix of larger particles through impact and friction processes or accumulate in complex glass-welded soil components (agglutinates) produced during repeated small impacts or heating events. Opaque particles of these sizes impose a strongly absorbing (darkening) effect with little or no wavelength dependence.

3. Optically active opaque (OAOpq) particles. These can include both npOpq and B-P particles as well as any group of dark or opaque particles of poorly characterized or undetermined properties. In short, this term can be used when the physical form of absorbing material is simply not known.

On a related matter, it should be noted that optically active opaque (OAOpq) particles are an inherent component in what many lunar petrologists simply call glass or amorphous optically dense material with no easily defined mineral components that often occurs in breccias or impact melt. When referring to glass, we strongly recommend adjectives also be used to define the actual type of material discussed. Quench glass in particular has distinctive and readily recognized optical properties [Bell et al., 1976], but such a material is not often found in lunar samples by optical techniques [e.g., Tompkins and Pieters, 2010]. Concentrations of quench glass principally occur as products of rapidly cooled pyroclastic volcanism such as orange glass 74220 and green glass 15401. The more common messy dark amorphous glass of lunar impact melt and breccias (see Tompkins and Pieters [2010] examples) can take on a range of optical properties depending on the actual character of its submicroscopic components which are almost never well characterized. In some cases the glass can be fully crystalline but at such a small scale to be unrecognized by most techniques. In other situations (perhaps most), the amorphous material is an unresolved mixture of npOpq and B-P particles intimately intermixed with crystalline material of a similar small size plus various amounts of residual uncrystallized glass. The bulk geochemical properties of such common dark amorphous material can readily be measured analytically, but its mineralogy (and consequently optical properties) is undetermined. Unraveling the complex composition and history of breccias and various forms of impact melt remains an important challenge to analytical techniques in the years ahead.

A key aspect of being able to detect alteration effects of space weathering processes is the ability of the regolith to accumulate and retain the space weathering products. All things being equal for a specific surface, a key variable is of course the time since the surface was formed. Also important, however, is the ability of the surface to retain and recycle a regolith that accumulates alteration products. This distinction is readily recognized in the lunar case where steep topographic slopes of older craters or prominent mountains/massifs are unable to collect a well-developed soil. These areas exhibit properties of an immature regolith, whereas nearby topographically flat areas with the same formation age exhibit well-developed or mature regolith. In a similar manner, small bodies with low mass are expected to be less able to retain and recycle regolith than larger bodies of the same composition and consequently small bodies accumulate less space weathering effects. For example, this was well illustrated with small S-type near-Earth asteroids < 5 km in size [Binzel et al., 2004].

Altogether, much has been learned about space weathering processes and products since the first return of samples from an airless planetary body. The lunar framework for understanding the magnitude and extent of space weathering products is now known to involve accumulation of optically active opaques. This
framework has met with reasonable success for understanding other solar system rocky bodies that are composed largely of anhydrous materials such as Mercury and some asteroids (S-type asteroid). However, in situations where an environment is able to only produce minimal OAOpq space weathering products (such as at Vesta), exogenic contamination and regolith mixing become the dominant processes of gradually altering optical properties of the regolith. This recognition that cross contamination among solar system bodies can often significantly affect the measured properties of surface material is an important lesson to highlight as we further explore solid bodies of the solar system.

On the other hand, documenting and identifying space weathering products and the alteration processes involved for surfaces of hydrous or volatile-rich bodies is much less understood. For most solid bodies we can only study the exposed surface with advanced remote sensing tools and model or constrain the observations with available laboratory experiments. We have initial observations of the presence of space weathering at Ceres and several hypotheses to test its origin. We recognize a diverse and extensive range of dark asteroids that are likely to contain a plethora of altered hydrous minerals or organic components, but their surfaces are not yet well explored. A wide range of volatile-rich or icy bodies exist, encompassing comets (and their offspring), Ceres, a multitude of satellites in the outer solar system, and even Pluto. As samples are returned from two dark (and presumed primitive) asteroids by Hayabusa-2 and OSIRIS-REx and increasingly sophisticated laboratory experiments are pursued, the next several decades of space weathering research will certainly clarify and expand our understanding of the mysteries and challenges that space weathering has placed before us across diverse conditions of the natural environment.

Acknowledgments

Data for this paper are properly cited, and specific files are identified in figure captions and can be found through the references identified or PDS. RELAB data can be found through http://www.planetary.brown.edu/relabdocs/relab.htm. We especially thank Lindsay Keller for contributing new TEM image (Figure 3b). The comments and suggestions by David Blewett and Paul Lucey were much appreciated and strengthened the final manuscript. This work has been supported through a NASA SSERVI cooperative agreement NNA14AB01A.

References


Blewett, D. T., and P. Lucey were much appreciated and strengthened the final manuscript. This work has been supported through a NASA SSERVI cooperative agreement NNA14AB01A.


Hiroi, T., C. M. Pieters, and H. Takeda (1994), Grain-size of the surface regolith of asteroid 4 Vesta estimated from its reflectance spectrum in comparison with HED meteorites, Meteoritics, 29(3), 394–396.


