SPACE WEATHERING ON MERCURY AND VESTA. P. K. Schelling[1], D. T. Britt[1], T. Bradley[1], and Guy J. Consolmagno SJ[2]. [1]University of Central Florida Department of Physics, P.O. Box 162385, Orlando FL 32816-2385, patrick.schelling@ucf.edu, [2]Vatican Observatory, V-00120 Vatican City State, gjc@specola.va.

Introduction: Space weathering refers to the chemical and morphological changes that occur due to direct exposure of minerals to the harsh space environment. The relevant mechanisms for space weathering include impacts (shock, vaporization, fragmentation, heating, melting, and ejecta formation), radiation damage and sputtering (due to cosmic rays or solar wind), and ion implantation (due to solar wind). Generally, the energy inputs leave the mineral surface depleted in volatile elements, thereby changing the composition near the surface. The classic example of space weathering is the formation of nanophase Fe ($npFe^0$) in the dusty lunar regolith [1,2]. The presence of $npFe^0$ on asteroids has been verified directly from material returned from 25143 Itokawa, and some asteroid classes do exhibit modest spectral red slopes characteristic of lunar-style space weathering [3].

However, much of our understanding of the processes and products of space weathering has been limited to analysis of lunar soils, and the possible weathering mechanisms and products occurring on other bodies in the solar system, including Mercury and Vesta, remains speculative. Based on remote sensing, it is becoming increasingly evident that insight based solely on what we understand about lunar-style space weathering does not present a complete picture. This makes characterization of the surfaces based on remote sensing alone challenging.

One of the key problems is that space weathering has primarily been explored in the context of the evolution of iron-rich silicate minerals, since the spectral red slope that emerges associated with $npFe^0$ is a distinctive feature. In cases where the composition of the weathered materials is different, and $npFe^0$ is not the most conspicuous weathering product, very little work has been done to understand what weathering products might be present. The products themselves might produce less dramatic spectral features in comparison to $npFe^0$. However, dramatic compositional and morphological evolution indeed should still occur, but progress in establishing space weathering products and mechanisms when $npFe^0$ is not the primary weathering product has been elusive.

In the present paper, we take a broad view of space weathering that suggests a way forward to making predictions about what weathering products might be present on bodies in the solar system, including Mercury and Vesta. Space weathering can be viewed as inputs of energy and matter that continually drives the surface composition out of equilibrium. As the system responds to changes in composition at the surface, chemical reactions and morphological changes are expected to occur. These include the formation and growth of $npFe^0$, but might be expected to include a much wider range of processes. For example, chemical reactions with other volatile elements, including, for example, hydrogen, water, and sulfur, could occur to establish a new chemical equilibrium. It should be possible to forward model the weathering process, using laboratory experiments, thermodynamic modeling, and atomic-scale simulation, to make predictions of how the chemical composition and morphology of regolith materials evolve over time. The basic approach is to use tools developed in the fields of materials science and physics, especially as applied to problems in surface science. By following this general perspective, we can hope to understand the formation processes of known weathering products, predict the formation of other products, and identify already well-known materials as the products of weathering reactions.

A General Theory of Space Weathering: Space weathering is driven by the continual input of energy occurring in the low oxygen fugacity of space. In the most general sense, the energy input results in compositional changes at the surface. The forward modeling of space weathering proposed here can be understood in terms of the thermodynamically-driven decomposition of common rock-forming minerals, resulting in the production of a wide range of daughter products:

(1) The silicate minerals generally become strongly reduced by preferential oxygen sputtering and possibly chemical reactions with embedded hydrogen.

(2) The decomposed metallic cations form nano-sized blebs, especially $npFe^0$, on the surfaces or in condensed rims of mineral grains.

(3) The liberated volatile elements and gases (e.g O, S, Na) may form an observable exosphere if sufficient quantities are available, e.g. Moon and Mercury, and can either escape from the body or react at mineral surfaces. For example, embedded hydrogen may react with oxygen to produce OH and H_2O. In fact, a trace amount of water has been observed on the lunar surface [4].

(4) Other volatile elements liberated from the surface can possible participate in chemical reactions on the surface to establish a new equilibrium composition

(5) Morphological changes occur due to sputter deposition and also migration of species and point defects occurring primarily at the surface.

Apart from thermodynamic driving forces that depend on the continual evolution of the surface composition, kinetic factors are also critical. For example, the growth of $npFe^0$ depends on the ability of Fe cation defects to migrate within the silicate. Similarly, reactions of volatile elements on the surface depend on kinetic factors, especially on the bonding of reaction intermediates at the surface. Hence, a complete understanding of space weathering, so that predictive models might be developed, depends not only on understanding the underlying thermodynamic driving forces, but also on the rates at which various processes might occur.

Space Weathering on Mercury and Vesta: Based on gamma and x-ray spectrometry, Vesta and Mercury regoliths present different compositions. Specifically, while pyroxene is thought to be an important component of both systems, Mercury is Fe-poor in comparison to Vesta [5] (Fe/Si=0.21 wgt% for Mercury, compared to 0.54 wgt% for Vesta, consistent with HED meteorites). Mercury shows evidence of strong weathering, $npFe^0$ formation, and even larger Britt-Pieters particles[6]. By contrast, Vesta, despite its higher Fe content, shows no evidence of $npFe^0$ in the near-IR spectra. It has been proposed that space-weathering mechanism on Vesta is mechanical mixing of diverse surface components[7]. However, it is also apparent that material exposed at fresh craters, while initially spectrally distinct, ages and eventually fades into the background of the surface regolith. This indicates that chemical changes are indeed happening on Vesta. However, the chemical evolution of Vesta regolith is poorly understood, and the apparent lack of $npFe^0$ has not been explained.

In addition to pyroxene, other mineral phases and compositions, including especially plagioclase feldspars (e.g. anorthite and orthoclase) are also thought to be important to both Mercury and Vesta[5,8]. However, space-weathering effects have not been systematically studied for these materials probably due to the fact that $npFe^0$ generally should not play a role. Specifically, the lack of Fe ions makes the feldspars more difficult to reduce with the corresponding evolution of elemental metal. However, changes in composition certainly are expected to occur, with weathering on Mercury closely connected to the content of the exosphere, including K, Ca, Mg, and Na.

Thermodynamics and kinetics: Improved understanding of both thermodynamic and kinetic factors can provide insight into features of space weathering on Mercury and Vesta that are distinct from lunar style space weathering. In the case of Mercury, we suggest that rapid growth of $npFe^0$ particles into larger Britt-Pieters particles likely is important. We propose that Ostwald ripening mechanism is controlling the growth of the Fe inclusions. The basic concept behind Ostwald ripening is the migration of ions in the matrix material, resulting in the growth of larger inclusions, with smaller inclusions shrinking or even vanishing. On Vesta, thermodynamic arguments suggest that chemical conditions might result in growth of FeS inclusions due to reactions with liberated S vapor. This mechanism might explain the apparent lack of $npFe^0$. It may be that FeS accumulates in rather larger inclusions, in contrast to the $npFe^0$ characteristic of lunar-style space weathering. In particular, the low eutectic temperature of FeS may promote local melting and growth of FeS clusters as a result of micrometeorite impacts.

Using atomic scale simulation, based on both density-functional theory and empirical potentials, key aspects of the relevant minerals have been elucidated that point to another important factor that might explain the unique weathering of Vesta. Specifically, we find significant differences between different silicate minerals, in particular pyroxene and olivine. We find healing of Frenkel defects caused by irradiation occurs primarily by migration of cation interstitials. However, simulations demonstrate that cation interstitials are more readily trapped in pyroxene in comparison to olivine. This may explains previously reported experiments that suggested olivine weathers more readily than pyroxene[9].

Implications: The application of insights from surface science, based on kinetic and thermodynamic factors, can lead to a new approach to predict weathering products. By developing combined experimental and computational approaches, predictions can be made that can be tested against other observations. In the case of Mercury and Vesta, several scenarios are presented that might explain unique weathering aspects. In particular, differences in kinetic factors, composition, and the presence of volatile elements including S, likely play an important role. In the case of kinetics, atomic-scale simulation can be used to determine clear differences in the kinetics of different weathering mechanisms, including especially the morphological changes that occur due to the migration and trapping of point defects.

References: [1] [2] [3] [4] Elsila, J.E., et al., (2012) MAPS 47, 1517-1536. [5] Mayne, R.G. et al. (2009) MAPS 45, 1074-1092. [6] Lucey, P. G. et al., (2011) Icarus 212, 451-462 [7] Pieters, C. M., et al (2012) Nature 491, 79-82 [8] Stockshill-Cahill, K. R., et al., (2012) J. Geo. Res.-Planets 117, E00L15 [9] Yamada, M. et al., (1999), Earth Planets and Space 51, 1255-1265