**SPACE WEATHERING ON VOLATILE-RICH ASTEROIDS.** D. T. Britt[1], P. K. Schelling[1], G. J. Consolmagno SJ[2], and T. Bradley[1]. [1]University of Central Florida Department of Physics, P.O. Box 162385, Orlando FL 32816-2385, britt@physics.ucf.edu, [2]Vatican Observatory, V-00120 Vatican City State, gjc@specola.va.

**Introduction:** Space weathering is a generic term for the effects on atmosphereless solid bodies in the solar system from a range of processes associated with direct exposure to the space environment. These include impact processes (shock, vaporization, fragmentation, heating, melting, and ejecta formation), radiation damage (from galactic and solar cosmic rays), solar wind effects (irradiation, ion implantation, and sputtering), and the chemical reactions driven by these processes. The classic example of space weathering is the formation of the so-called lunar spectral red slope associated with the production of nanophase Fe ($npFe^0$) in the dusty lunar regolith [1,2]. Similar $npFe^0$ has been recovered from asteroid 25143 Itokawa and some asteroid classes do exhibit modest spectral red slopes [3].

But our understanding of the processes and products of space weathering has been limited by our access to pristine samples like the lunar soils returned by the Apollo program and our necessarily limited view of surfaces provided by telescopic remote sensing. We have primarily focused on the most obvious aspects of weathering, such as the lunar red slope, but our limited data has also limited our view of this essentially physical and chemical phenomena.

However, there is another way to explore space weathering that is not limited by observations or available pristine samples. Space weathering can be viewed as the response of surface materials to energetic inputs that continually drive the surface composition away from equilibrium, resulting in chemical reactions and morphological evolution that can be understood from these underlying thermodynamic driving forces. By using techniques and insight developed in the context of materials science and physics, especially related to surface science, we can assess the environment of the common asteroidal and planetary materials and forward model the expected results of the weathering reactions. This approach can help us 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 a combination of the chemical environment of space (hard vacuum, low oxygen fugacity, solar wind implantation of hydrogen) along with thermal energy supplied by micrometeorite impacts. The forward modeling of space weathering as thermodynamically-driven decomposition of common rock-forming minerals suggests the production of a range of daughter products:

(1) The silicate products typically lose oxygen, other volatile elements (i.e. sulfur and sodium), and metallic cations, producing minerals that are typically more disordered and less optically active than the original parent materials.

(2) The decomposed metallic cations form in nano-sized blebs including $npFe^0$, on the surfaces or in condensing rims of mineral grains. This creates a powerful optical component as seen in the lunar red slope. Surfaces with exposed $npFe^0$ are an ideal environment for catalyzing further reactions.

(3) The liberated volatile elements and gases (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 recombine with available solar wind implanted hydrogen to form trace amounts of water and OH. Such trace amounts of water has been observed on the lunar surface [4].

Mineral decomposition can be thought of as the first stage of space weathering. It produces weathered (i.e. strongly reduced) surfaces somewhat depleted in volatile elements, creates a predictable set of minor or trace minerals, and leaves the surfaces with catalytic species, primarily $npFe^0$. However, a second stage of further reactions and weathering depends upon the presence of “feedstock” components that can participate in catalyzed chemical reactions on exposed surfaces.

**Weathering on Volatile-Rich Asteroids:** In the case of the lunar regolith, the feedstock is largely missing and the surface simply accumulates $npFe^0$ possibly with the production of water. It is notably highly reactive, but further reactions are limited by the absence of volatiles.

However, the weathering situation and products are expected to be substantially different in volatile-rich small bodies. For these bodies, the available materials are not only silicates, but a volatile feedstock that can include water, carbon monoxide, ammonia, to name a few. As in volatile-poor surfaces, thermodynamically-driven decomposition of silicates will produce trace amounts of $npFe^0$ which are ideal sites for Fischer-Tropsch type (FTT) catalytic reactions that can produce organics *in situ* on the asteroids. Thus FTT and other catalytic reactions that occur as a direct result of space weathering will produce the large range of organic materials found in volatile-rich carbonaceous meteorites including alkanes, polyaromatic hydrocarbons, and amino acids [5]. The mix and range of products depends on the composition and morphology of the mineral surface, energy inputs produced by the micrometeorite impacts or other processes, and the composition of the input volatile feedstock.

**Fischer-Tropsch Synthesis:** FFT synthesis generally refers to chemical reactions that convert CO and $H_2$ into liquid hydrocarbons and $H_2O$, for example,

$$n\,CO + 2n\,H_2 \rightarrow (-CH_2-)n + nH_2O$$

Industrially, reactions of this kind are used to generate liquid hydrocarbon fuels from coal; iron is often used as a catalyst material [6]. The basic role of the catalyst is to bind reaction intermediates and thereby lower the energy barriers for breaking bonds and forming products. Generally, iron catalyst is introduced as an oxide, but the catalyst is activated by reduction at high temperature in an $H_2$/CO environment.

There have been several reports of organics generated by FTT processes. It has been shown that a wide spectrum of organic molecules can be generated using either iron meteorite or motmorillonite clay, and CO, $H_2$, and $NH_3$ as reactants [7]. It has generally been postulated that FTT reactions might have been active in the solar nebula [7, 8]. Yet validation of FTT reactions in the solar nebula as the source of the observed organics has remained elusive [9, 10]. One difficulty is that there is no clear mechanism for preserving organics during condensation of asteroid material [11].

Though there have been problems in validating the FTT process in the solar nebula, one can consider reactions that could occur *in situ* on asteroid surfaces. The necessary catalysts may not have existed in the solar nebula gas and dust, but rather evolved after the formation of the asteroids. Specifically, we hypothesize that the energy inputs responsible for space weathering will also activate the catalytic properties of early weathering products on asteroid surfaces.

The usual mechanisms for space weathering, including micrometeorite bombardment, provide heat to drive the reactions. Reducing conditions can come from either the low oxygen fugacity of hard vacuum or from solar wind implanted hydrogen, either of which should act to drive FTT reactions. The chemical reactions themselves are expected to occur primarily at $npFe^0$ inclusions, but secondary reactions may also occur in the supporting mineral matrix.

As suggested above FFT reactions generate long-chain carbon compounds and amino acids. Secondary reactions likely occur as the organic material matures. Weathering maturity can be thought of as a function of the abundance and diversity of the weathering products. Since the $npFe^0$ is not destroyed in the reaction, continued micrometeorite bombardment would result in continuing processing and recombination of the existing organic feedstock. More weathering would result in progressively longer-chain carbon compounds as well as more complex and diverse amino acids, and eventually the kerogen-like insoluble-organic matter that forms a large fraction of carbonaceous meteorites.

**Implications:** This insight has several major implications for our view of planetary science and, potentially, the formation of the precursors of life. First, the range of weathering products that we see in remotely sensed data, meteorites, and returned samples are not random, but the predictable outcome of the source region's mineral kinetics and chemical feedstock. Weathering products do not have to be optically active like the $npFe^0$ that produces the lunar red slope; on the contrary, probably most weathering products are spectrally neutral or even suppress an object's reflectance spectrum (Note that organic material and water have distinct spectral signatures, but mostly observable in infrared spectra beyond 2 microns).

In the case of volatile-rich parent bodies, a major weathering product is a range of carbon-rich compounds. But as an additional result of considerable interest, the generation of pre-biotic compounds is a routine and predictable byproduct of common space weathering processes. Any atmosphereless body around any star with mineral compositions and volatile feedstocks, such as what we think are common in the universe, should create amino acids as a routine by-product of space weathering. The precursors of life are probably abundant in any space-weathered asteroid belt, in any solar system, and only wait being accreted to a hospitable environment.

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