Space-weathering processes and products on volatile-rich asteroids

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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 lunar spectral red slope associated with the production of nanophase Fe (npFe0) in the dusty lunar regolith (C.R. Chapman, 2004, Annual Review of Earth & Planet. Sci. 32, C.M. Pieters, 2000, MAPS 35). Similar npFe0 has been recovered from asteroid (25143) Itokawa and some asteroid classes do exhibit modest spectral red slopes (T. Noguchi, 2011, Science 333).

Space weathering can be thought of as 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 npFe0, 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 npFe0 are an ideal environment for catalyzing further reactions. (3) The liberated volatile elements and gases (O, S, Na) may form an observable exosphere (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.

Mineral decomposition can be thought of as the first stage of space weathering. It produces weathered surfaces somewhat depleted in volatile elements, creates a predictable set of minor or trace minerals, and leaves the surfaces with catalytic species, primarily npFe0. However, a second stage of further reactions and weathering depends upon the presence of ”feed-stock” components that can participate in catalyzed chemical reactions on exposed surfaces.

For volatile-rich small bodies, the available materials are not only silicates, but a volatile feedstock that can include water, carbon monoxide, ammonia, to name a few. Thermodynamically-driven decomposition of silicates will produce trace amounts of npFe0 which are ideal sites for Fischer-Tropsch type (FTT) catalytic reactions that can produce organics in situ on the asteroids including alkanes, polyaromatic hydrocarbons, and amino acids (J.E. Elsila, 2012, MAPS 47). 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.

FFT reactions generate long-chain carbon compounds and amino acids. Secondary reactions that generate more complex carbon compounds and amino acids are likely to 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 npFe0 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.

This insight has several major implications for our planetary science and, potentially, the formation of the precursors of life. First, the range of weathering products seen 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 npFe0 that produces the lunar red slope; on the contrary, probably most weathering products are spectrally neutral or even suppress an object's near-IR reflectance spectrum.

In the case of volatile-rich parent bodies, a major weathering product is a range of carbon-rich compounds. But an additional result of considerable interest is the generation of pre-biotic compounds as a routine and predictable byproduct of common space-weathering processes. Any atmosphereless body around any star with mafic silicate mineral compositions and volatile feedstocks should create amino acids as a standard byproduct 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.