Interplanetary Weathering: Surface Erosion in Outer Space

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Introduction

What happens to bare rock and icy surfaces as they lie exposed to the interplanetary space environment for millions of years? This fundamental question has important implications for the interpretation of remotely sensed data, whether obtained telescopically or by spacecraft. It turns out, of course, to be a very difficult question to answer.

The Apollo astronauts scraped the surface of the moon and brought back samples of the surface soils and of the underlying rocks. These lunar samples have been our most valuable resource to date for studying the space weathering question. The lunar surface soils differ from their source rocks in at least one very important way: they look different. For eons, the surface soils have been bombarded by meteoroids and micrometeoroids, by solar UV photons, by solar wind and solar flare ions, and by galactic and extra-galactic cosmic rays. These processes can result in structural, chemical, and physical changes to planetary surfaces, lunar and otherwise, over time (see Figure 1).

Extensive spacecraft and orbital telescope studies (*e. g. Voyager, Hubble* and the *IUE*) of the outer solar system have generated interest in a different class of 'weathered' surface: the icy surfaces of the moons of the giant planets. Although ice is the 'rock' of small outer solar system objects, it is inherently more volatile than silicates, and, hence, icy surfaces are more easily altered – resulting in time scales for surface maturation which are very different than those on the moon.

Ice and rock are not the only surfaces affected by weathering in the space environment; even microscopic space 'dust' is vulnerable. Recently, Earth orbiting spacecraft (*e.g.* LDEF) and U2 aircraft have collected Interplanetary Dust Particles (IDPs) from the uppermost layers of Earth's atmosphere. These tiny particles, thought to be asteroidal and cometary in origin, have been extensively weathered by interactions with energetic charged particles since their release from their parent object (Bradley 1994).

Directions in Research

We are now beginning to understand space weathering processes and how they affect lunar soils and interplanetary dust. However, problems lie in extrapolating these processes to the asteroids, Mercury, the Galilean Satellites of Jupiter, *etc.* and predicting their effects on optical properties. Issues currently under discussion by scientists are focused on four central themes: 1) Processes and Products; defining the leading model for lunar surface alteration and quantifying its effects; studying the production and composition of altered materials, transient atmospheres, coronae and levitated dust layers; 2) Experiments; results from particulate bombardment simulations and ion and photon irradiation; 3) Predictions; extrapolation of experimental, lunar, IDP and meteorite data to other surfaces, and 4) Compensation; developing methods to "see" through the weathering and understand the underlying geology. To achieve this ultimate goal, the competing weathering processes and their effects and rates of occurrence must be formalised.

Data from NASA's *Near-Earth Asteroid Rendezvous* mission (NEAR) is anticipated to answer some of the questions regarding space weathering of rocky surfaces. Similarly, the *Galileo* and *Cassini* spacecraft results for the icy moons of Jupiter and Saturn will help enormously to resolve space weathering questions about icy surfaces. However, while awaiting new spacecraft data, we continue to interpret lunar and IDP data, and to push forward on theoretical and experimental simulation of weathering processes. Space weathering has reached the forefront of remote spectral studies and was the subject of a special session at the Spring 1995 meeting of the American Geophysical Union. Planetary geologists and fields and particles physicists are working together to understand the interdisciplinary nature of space weathering. The following is a summary of the current status of problems and research within the space weathering community, a cross-disciplinary subfield of space physics.

The Moon

The most comprehensive model to date for lunar surface alteration has been summarized by B. Hapke (University of Pittsburgh). According to this model, impacts and solar wind sputtering on the moon result in the production of a melt and a vapor phase from target materials (Housely et al. 1974, Hapke 1993, Keller and McKay 1993). The amount of vapor phase material which is produced and redeposited on the lunar surface is comparable to the amount of melt material. In the reducing chemical environment of the lunar near surface, Fe^{2+} is reduced in the melted materials and forms submicroscopic iron metal particles in the resulting glass. Subsequent redeposition of vapor results in coatings, containing submicroscopic reduced iron, on surface mineral grains. It is this submicroscopic iron which appears to be responsible for the optical changes occurring to rock exposed on the lunar surface.

Experimental simulations of lunar surface processes explored by C. Allen and colleagues (Lockheed Martin and Johnson Space Center, Houston), have verified that the optical effects characteristic of space weathering can be simulated by high-temperature hydrogen reduction (Allen et al. 1993, 1995). The experiments produce submicroscopic iron metal particles in glass and FeO- bearing minerals. These particles serve to decrease the overall sample albedo, lower spectral contrast, and increase the visible/near infrared continuum slope. Charged particle irradiation effects (e.g. Johnson and Baragiola 1991), although present in the form of amorphous rims and solar flare tracks, do not appear to be the main controls of lunar optical properties.

Using detailed analyses of actual returned lunar soils in conjunction with imaging data from the *Clementine* spacecraft, E. Fischer (Brown University) has developed a method for mathematically removing surface effects from lunar multispectral data. Once the signature of weathering is removed, Fischer has shown that accurate maps of subsurface lunar 'bedrock' are possible. This exciting and important result will undoubtedly be interesting and helpful to planetary geologists who work with remote sensing techniques. In particular, C. Pieters (Brown University) is investigating the causes of varying rates and competing processes for surface modification on Mercury, the Moon, and the Asteroids.

Also of interest is the recent work of P. Lucey and colleagues (University of Hawaii), who have applied removal techniques of space weathering effects to the global lunar images from the *Clementine* data. Once the iron produced by surface alteration effects was removed from spectral determinations of total iron, Lucey et al. discovered that the moon is enriched in iron-bearing minerals compared to the Earth. This finding excludes models for lunar origin that require the Earth and moon to have the same compositions, such as fission and coaccretion, and favors the giant impact and capture scenarios (Lucey et al. 1995).

For the moon, at least, we have come far in understanding surface alteration effects and have used this understanding to "see" through the weathering. These advances in remote sensing determinations have led to important conclusions about the geology and the formation of our moon.

Mercury

Mercury has been predicted to be strongly affected by alteration due to impact melting of surface materials. A study by M. Cintala (NASA Johnson Space Center) shows higher predicted fluxes of impactors as well as higher expected impact velocities, a set of conditions which should conspire to significantly bombard surface rocks, possibly resulting in glass and agglutinate formation. Due to its high temperatures, reflected light compositional studies of Mercury are difficult at best, and it is possible that they are further complicated by intense space weathering alteration of surface grains (Cintala 1993).

Corroborating such predictions are theoretical studies of space weathering effects at Mercury performed by W. Smythe (Jet Propulsion Laboratory) and colleagues. Noting the apparent lack of oxidized iron absorption features in Mercury's spectrum, Smythe et al. (1995) offer three physical processes which can account for this result. First, dayside-nightside temperature contrasts could produce finely divided grains at the optical surface, decreasing absorption band depths if they exist. Second, the high solar flux produces a surficial regime of hot atom chemistry and, thirdly, when combined with reducing conditions due to high hydrogen fluxes, could result in chemical reduction of iron without invoking heat supplied from impactors.

Mercury has traditionally been expected to have as much iron in its rocks as the Earth's moon, but several recent observational studies have indicated otherwise (Mitchell and de Pater 1994, Sprague et al. 1994, Vilas et al. 1984) Observing Mercury in the midinfrared (5-14 microns) from the Kuiper Airborne Observatory, A. Sprague (University of Arizona) and colleagues have noted possible optical maturation effects in the details of their emission spectra compositional studies. The magnitude of the effects was small and did not preclude the use of mid-ir spectroscopy to determine surface composition. Sprague et al. concluded that Mercury's surface is plagioclase-rich and possibly basaltic in composition, consistng of minerals more depleted in oxidized iron than those on the moon (Sprague et al. 1994).

It thus seems that compositional studies of Mercury are heavily influenced by space weathering issues. Varying assumptions regarding surface processes and products are the main cause for controversy over what Mercury is made of.

The Asteroids

Very recently, dramatic evidence for asteroidal surface alteration has been seen in the *Galileo* spacecraft imaging data of asteroids 951 Gaspra and 243 Ida (see Figure 2). These images are the first glimpse of *in situ* asteroidal response to space weathering and constitute the first clear evidence that low-gravity rock surfaces are modified through time (Sullivan et al. 1996). The big question now is – what process is altering the surface and how does it work? Unfortunately, it seems that a straight-forward extrapolation of the lunar model of surface alteration cannot explain the asteroid data.

In particular, B. Clark (University of Arizona) has shown how infrared spectral data of asteroids and their mineral components create problems in interpreting asteroid surfaces using the lunar model. Most troubling is the fact that the spectroscopic data are not consistent with lunar-like space weathering effects to explain the infrared spectral differences between asteroids and their proposed meteorite analogs (Clark 1996). This means that a new and different model, sensitive to target composition, must be developed for asteroid space weathering in order to proceed in explaining the geology and meteorite associations of the main belt asteroids.

Seeking to understand the meteorite record of optical surface alteration processes, D. Britt (University of Arizona) has examined shock darkened and solar-wind implanted gas-rich ordinary chondrite meteorites. Britt suggests that these meteorites retain actual materials which resided at the asteroidal optical surface in the past, and that study of their properties is crucial to understanding meteorite-asteroid spectral linkages (Britt et al. 1989). So far these studies have led to some predictions which have yet to be verified, and it may be that final verification will have to await an asteroid sample return mission.

However, in an important effort to simulate weathering processes which may currently be affecting asteroid surfaces in space, L. McFadden (University of Maryland) with C. Dukes and R. Baragiola (University of Virginia) are experimenting with irradiation effects on minerals. These experiments are aimed at understanding chemical changes due to irradiation and their possible correlation with reflectance changes. Using photoelectron spectroscopy they have obtained quantitative measurements of chemical reduction which may occur due to solar wind ion bombardment. The degree to which these chemical changes affect optical properties is being examined to ascertain their importance for the spectroscopic appearance of asteroids.

For the asteroids, therefore, it has not yet been determined what mechanism or combinations of mechanisms are responsible for the apparent surface alteration seen in the Galileo data (Sullivan et al. 1996).

Laboratory simulations are proceeding and the meteorite record is being scrutinized, but the complications of having many meteorite samples from many lithologically different asteroid source bodies promises to keep investigators busy for some time to come. The problems of relating asteroid spectra to meteorite spectra are far from settled, as evidenced by the exciting special session debate between J. Bell (University of Hawaii) and C. Chapman (Southwest Research Institute) at the most recent American Astronomical Society Division for Planetary Sciences meeting, held in Hawaii in October 1995.

Interplanetary Dust Particles

Irradiation effects actually found *in situ* on Interplanetary Dust Particles are being studied by J. Bradley (MVA Incorporated). So far Bradley has discovered that ionizing radiation causes major structural and compositional changes to IDPs (Bradley 1994). In particular, silicate minerals are amorphized, foreign elements are implanted, cations are selectively removed, and specific elements are enriched. These chemical changes may be important components of the optical changes occurring on bare mineral surfaces. In fact, Bradley has found nanoscale inclusions within the IDPs that may have been 'weathered' by charged particles in the interstellar medium.

It is possible that our best understanding of the microphysical effects possible from weathering in the space environment will come from the study of these IDPs. If it turns out that the chemical changes wrought by ionizing radiation significantly affect optical properties, then this mechanism and its rate will have to be included in the equation of competing alteration mechanisms.

Transient Effects

An indirect but potentially valuable diagnostic tool for determining planetary surface compositions is the identification and measurement of relative abundances of gases sputtered, vaporized, or outgassed from surface materials. These studies have been especially interesting on Mercury and the Moon, where Na and

K have been positively detected in the form of a transient 'atmosphere' above the surface.

A. Sprague and D. Hunten (University of Arizona) have studied the relative production rates of atomic species to the lunar and mercurian atmospheres, and have compared their theoretical predicted rates due to various physical processes, including space weathering, to observational constraints (Sprague and Hunten 1994). They conclude that impact vaporization of both impactor and surface materials is a probable supply mechanism for the Na and K, but note that models are non-linearly dependent on temperature.

T. Morgan and R. Killen (Southwest Research Institute) with A. Potter (NASA/Johnson Space Center) have recently reported on observation and modelling efforts to describe the composition of the coronae of Mercury and the Moon. Morgan and colleagues conclude that ion sputtering plays an important role in the ejection of Na atoms, and they have developed models for other species in the hope of using the observational data to constrain surface composition (e.g. Morgan and Killen 1995). B. Flynn and A. Stern (Southwest Research Institute) have carried out a ground based spectroscopic survey to put upper limits on the metallic species in the lunar atmosphere which may be produced by ion sputtering. With their observations, they have detected non-stoichiometric relative abundances of metals, and they conclude that the mechanisms which produce the lunar Na and K atmosphere may somehow distinctly favor these species over more or comparably abundant lunar surface species (Stern and Flynn 1995).

It has been suggested that with sufficient levels of ionizing radiation it may be possible to cause the ejection and levitation of molecule sized particles at an atmosphereless surface. Although this mechanism has not been widely accepted, the possibility remains that there are effects on optical properties from dust levitation at an asteroidal surface due to charging by solar ions, electrons and UV photons. A. Cheng (Johns Hopkins University) has suggested that data from the NEAR mission will serve to test the feasibility of this mechanism.

Icy Moons

Whereas the effect of charged particle weathering on the optical properties of refractory surfaces is not fully established, the effects on icy moon surfaces in the outer solar system have been well studied. R. Johnson (University of Virginia) has described a number of observations attributed to ion-induced weathering of the icy moons. Although subtle, the effects can be clearly seen in reflectance changes with longitude (e.g. Johnson 1990). The orbits of icy moons at Saturn and Jupiter are phase-locked to and the plasma co-rotates with the parent planet, and because of this peculiar geometry, the ion bombardment rate varies with longitude resulting in longitudinal variation in reflectance. The changes produced by ion bombardment compete, as usual, with other weathering processes such as micrometeorite vaporization and regolith agitation. The icy moons are thus excellent 'laboratories' for studying the dynamics of space weathering. R. Baragiola (University of Virginia) has described laboratory studies of ion and UV photon irradiation of ices to quantify the optical alterations seen on the icy moons (Baragiola and Johnson 1995). These data are useful in the interpretation of O^2 trapped in the surface ices on Ganymede (Spencer et al. 1995) as well as the sputter-produced ambient OH near Tethys (Shemansky et al. 1993) and O^2 corona on Europa (Hall et al. 1995), both recently seen with the *Hubble Space Telescope.* These neutral coronae, produced by weathering, are comparable in extent to the Na and K coronae at Mercury and the Moon.

Conclusion

In conclusion, it is clear that weathering processes in the space environment are important surface alteration mechanisms. Given time, bombardment processes can alter the nature of refractory and icy surfaces. Understanding space weathering mechanisms and their effects is thus a desirable prelude to the interpretation of remote sensing of planetary surfaces.

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