QUANTITATIVE ASPECTS OF SPACE WEATHERING: IMPLICATIONS FOR REGOLITH BRECCIA METEORITES AND ASTEROIDS.

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Introduction: Space weathering is defined as the physical and optical changes incurred by material exposed to the space environment. Through studies of lunar soils, these changes are becoming well understood [1,2]. However, the effects of space weathering are dependent on the physical environment to which the host materials are exposed, and thus, the effects will likely vary from body to body.

The optical effects of space weathering result from nanophase iron (npFe^0) created during micrometeorite bombardment and solar wind sputtering [1,3]. In the asteroid belt, bodies are farther from the sun than our Moon, and are widely known to incur less solar wind implantation and sputtering. The velocity of impacts is smaller resulting in less melting and vaporization, and therefore fewer space weathering products. The impact rate in the asteroid belt is greater, which will result in more comminution, further diluting any weathering products. Ergo, asteroidal regoliths should contain fewer space weathering products than lunar soils. However, even very small degrees of space weathering can have dramatic consequences for the optical properties of soils [4].

The Optical Effects of Space Weathering: The optical effects of space weathering are often summarized as making the reflectance spectra of a soil darker, redder, and causing an attenuation of absorption bands [5]. While true, this three-fold effect is an oversimplification of the weathering process. We have shown that the precise expression of these changes will vary as a function of npFe^0 content.

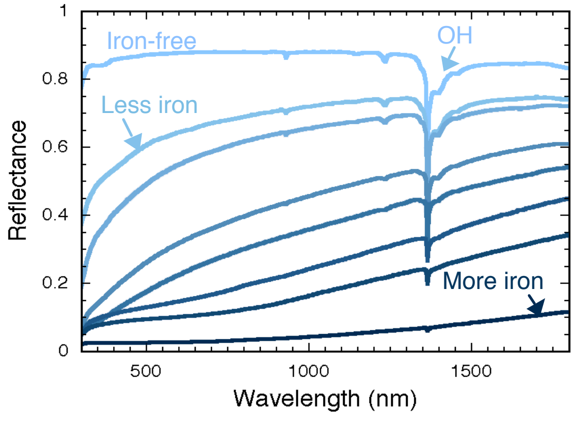

Figure 1. Reflectance spectra of npFe^0-impregnated silica gel powders. The top spectrum contains no iron. The remaining spectra contain various amounts of ~10nm dia. npFe^0 with iron content increasing as reflectance decreases.

In order to quantify the influence of the npFe^0 concentration on optical properties, an analog material was synthesized by impregnating silica gel powders with npFe^0 [6]. The spectra of these powders, with a varying concentration range of ~10nm diameter npFe^0, are shown in Fig. 1. These results are consistent with the modeling results of Hapke [1] and previous experimental results [7]. It is clear from this suite that adding significant amounts of iron (>0.5 wt%) does result in an overall reddening and darkening throughout the Vis/NIR region. By contrast, adding only very small amounts (<0.1 wt%) of npFe^0 results in a steep convex curvature in the visible region, while leaving the near infrared virtually unaffected.

This pattern was first noticed in the finest fraction of weathered lunar soils [8]. Because npFe^0 is concentrated in rims on grain surfaces, the optical properties of the finest fraction of soils, with their greater surface to volume ratio, are dominated by space weathering effects. Immature and submature highland soils and immature mare soils display the distinct curvature in the visible, while more mature soils with higher npFe^0 contents have spectra which are significantly darker and nearly linear in shape. In Fig. 2 are examples of a highland soil with a highly curved continuum and a mare soil with a much darker and more linear spectrum.

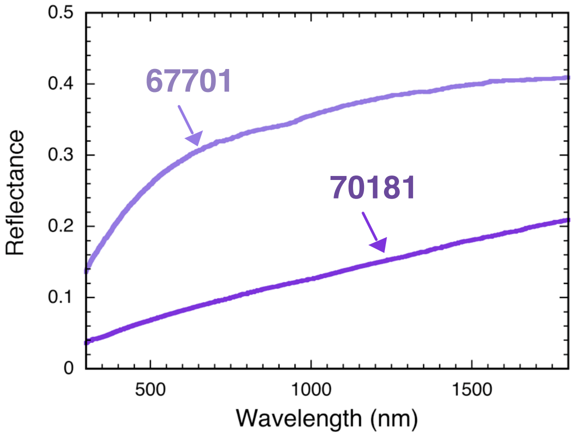

Figure 2. Reflectance spectra of the <10μm size fraction of two submature lunar soils: a highland soil (67701) and a mare soil (70181).

Asteroids: There has been much discussion in the asteroid community about the effects of space weathering on asteroids. As stated earlier, the environmental conditions at the asteroid belt are clearly different than the lunar environment, suggesting that asteroids should produce fewer space weathering products than the moon. However, there is certainly spectral evidence that space weathering is active on asteroids. For example, Galileo data indicates a reddening of Ida and Gaspra surface regolith with time [9]. Binzel *et al.* [10] report that among S-type near-earth asteroids a continuum exists from bodies that spectrally resemble ordinary chondrites to those with classic S-type spectra, consistent with an ongoing alteration process. In fact, the systematic differences between the spectra of asteroids and their meteorites counterparts corresponds well to what is expected for very small amounts of space weathering [2], a strong reddening in the visible, but less reddening at longer wavelengths compared to lunar soils.

Meteorite Regolith Breccias: We have no direct asteroid surface regolith samples to study, but some meteorites show evidence that a fraction of their constituent grains were directly exposed at the asteroid surface. Studies of lunar regolith breccias [11] indicate that space weathering products, in particular, npFe^0-bearing rims, are easily preserved through lithification, thus meteorite regolith breccias provide an opportunity to directly observe evidence of space weathering on asteroids.

The regolith breccia Kapoeta is a howardite, a basaltic achondrite, derived from a differentiated body, probably asteroid 4Vesta. Kapoeta is a class A breccia that contains implanted solar wind gases, micro-craters, and other evidence of surface exposure; though it has been estimated that not more than ~20% of the grains in such a breccia were directly exposed at the surface [12].

SEM observations of several Kapoeta thin sections revealed melt products in the form of both spherules (Fig. 3) and glass rims, though no equivalent to lunar agglutinates was identified. While melt products are less common in the meteorite breccias than in their lunar counterparts, it is clear that even at the lower impact velocities of the asteroid environment, melt is created.

TEM observations of two ion milled sections extracted from the same thin section revealed one possible npFe^0-bearing rim (Fig. 4). The rim surrounds over 50% of the grain and contains a nano-scale opaque phase, presumably npFe^0. The identification of a single rim underscores two points: (1) weathering rims *are* created in asteroid regolith, and (2) such rims are *very* rare and difficult to find.

Conclusions: The environment at the asteroid belt is such that only very small amounts of space weathering are expected. The rarity of weathering products in regolith breccia meteorites relative to their lunar counterparts confirms this expectation. The optical effects of very small degrees of space weathering differ substantially from the more general reddening/darkening effects of larger amounts of weathering. Small degrees of weathering more strongly influence the visible region of the spectra, while leaving the near-IR largely unaffected. These trends account for most differences observed between meteorite and asteroid spectra.

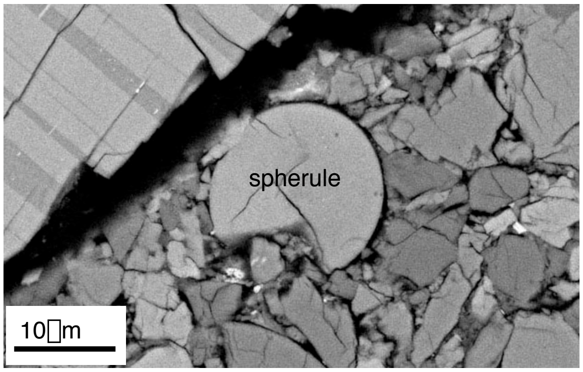

Figure 3. SEM image of a spherule (melt droplet) in the howardite Kapoeta.

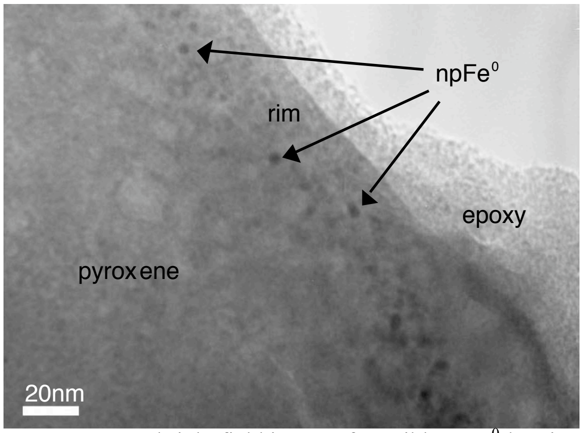

Figure 4. TEM bright field image of possible npFe^0-bearing rim on a pyroxene grain in the howardite Kapoeta.

References: [1] Hapke. B. (2001) *JGR,* **106** E5 10,039-10,073. [2] Pieters C. M. *et al* (2000) *MAPS,* **35**, 1101-1107. [3] Keller L. P. and McKay D. S. (1997) *GCA* **61**, 11, 2331-41. [4] Noble S. K. *et al.* (2004) *JGR* in prep [5] Pieters C. M. *et al* (1993) *JGR* **98**, 20,817-20,824. [6] Noble S. K. *et al* (2003) *LPSCXXXIV* ab#1172. [7] Allen C. C. *et al* (1996) *LPSCXXVII* 13-14. [8] Noble S. K. *et al* (2001) *MAPS,* **36**, 31-42. [9] Chapman C. *et al* (1997) *MAPS,* **31**, 699-725. [10] Binzel R. P. *et al* (1996) *Science,* **273**, 946-948. [11] Noble S. K. *et al* (2003) *MAPS,* **38**, A56. [12] Macdougall J. D. (1983) *LPI Tech Report* **82-02**, 94-96.

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