SPACE WEATHERING AND THE ANALYSIS OF ASTEROID REFLECTANCE SPECTRA. M. J. Gaffey, Department of Space Studies, University of North Dakota, Box 9008, Grand Forks, ND 58202-9008. Email: gaffey@space.edu.

Introduction: A basic goal of asteroid studies is to understand the thermal and chemical processes involved in the formation and geochemical evolution of early solar system bodies. The mineralogical and chemical characterizations of asteroids and their meteoritic samples provide our only direct information on the conditions and processes which were present in the inner solar system during the formation epoch. It is important to understand to what extent proposed and/or observed space weathering processes would affect our ability to extract mineralogical and compositional information from asteroid spectra.

Space Weathering: Space weathering is the generic term for the processes that modify the optical properties of surfaces of bodies exposed to the space environment. Its effect on the interpretation of asteroid spectral data and on potential asteroid-meteorite links has been an area of considerable discussion for more than three decades [e.g., 1, 2 and references therein]. The question has been whether or not space weathering affects the interpretations of asteroid spectra. The answer is both "yes" and "no" depending on the interpretive technique.

The best understood example of space weathering is Lunar-style space weathering. The importance of space weathering on the Moon was well documented by the examination of the reflectance spectra of the lunar samples returned by the first Apollo missions [e.g., 3]. With increased weathering, the spectra of lunar soils exhibit systematically lower albedos, weaker mineral absorption features, and redder spectral slopes than the bedrock lithologies from which they were derived. In this context, "red" means increasing reflectance with increasing wavelength, not the color "red".

The Lunar-style space weathering process modifies the spectral slope, band intensities, and albedo of soils on the lunar surface. The mechanism involves the presence of tiny (~4-30 nm) metallic iron grains (nanophase metallic iron, or $npFe^0$) in thin layers or patinas of glass coating the surfaces of lunar soil grains [4-7]. In discussions of the $npFe^0$ model for lunar space weathering, it was also concluded that this mechanism was important on asteroid surfaces and that it potentially allowed large numbers of ordinary chondrite parent bodies to be present in the asteroid belt [4,7].

Asteroid Space Weathering – The Concept: The issue of asteroid space weathering has been intimately associated with the search for the parent bodies of the ordinary chondrites (OCs). Initially, many investigators made the logical assumption that an abundant meteorite type (OCs make up ~75% of all meteorite falls) should derive from an abundant asteroid type. The common S-type asteroids (which contain the same general suite of minerals found in ordinary chondrites) seemed to be the best candidate.

However, the S-asteroid spectra exhibited significantly weaker mafic mineral absorption features and overall reddish spectral slopes relative to the spectra of ordinary chondrites. This mismatch between S-asteroid and ordinary chondrite spectra was not only a puzzle to the asteroid investigators but a serious impediment to understanding the nature of the early solar system.

Lunar style space weathering provided an easy "fix" for the problem. Starting with the assumption that ordinary chondrites should come from the common S-type asteroids, it was a simple step to invoking space weathering to modify the spectra of ordinary chondritic materials to resemble the S-type asteroids. Since space weathering of lunar samples weakened the absorption features and reddened the spectra, the weaker absorption features and redder spectra of the surfaces of S-type asteroids could be reconciled with space weathered ordinary chondritic assemblages. Thus the initial justification for asteroid space weathering studies rested primarily on an assumption about the relationship between asteroids and meteorites.

Asteroid Space Weathering - Observed: There appears to be no doubt that the surfaces of asteroids are altered by exposure to the space environment. High resolution images of the surface of 433 Eros shows albedo patterns expected for space weathering. As in the case of the lunar surface, downslope movement of material appears to expose higher albedo, less weathered material, while the darker weathered material accumulates at the base of the slope.

Although a lunar space weathering process has been invoked for asteroid surfaces, it is evident that there are serious problems with this. On 433 Eros, there are albedo variations of up to a factor of five with only small (~10%) color variations across the surface (Figure 16 in [8]). Moreover, the Eros color – albedo trend is oriented toward a very different end point than the Lunar color – albedo trends for either highland or mare regions [8]. There are no detectable variations in absorption band depths at a limit of $\pm$2% [9].

By contrast, 243 Ida, a Galileo flyby target, shows large (approximately a factor of two) variations in the absorption band depths across the surface but no discernable variation in surface albedo [10,11].

Figure 1 compares the space weathering trends on asteroids 243 Ida and 433 Eros to that on the moon. It is evident that different processes are operating on each of these three bodies. The effects of space weathering on the surface of 433 Eros were "both qualitatively and quantitatively different than in the lunar maria" [8].

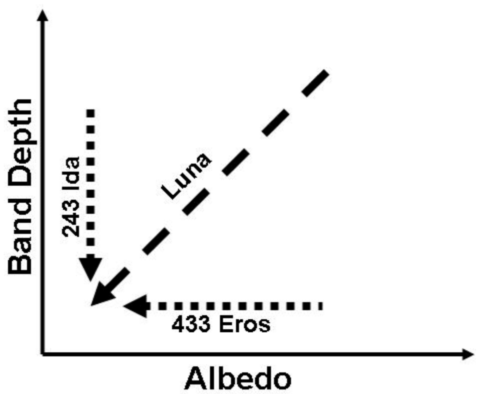

Figure 1 – Schematic representations of spectral-albedo correlations for the optical surfaces of the Moon and asteroids 243 Ida and 433 Eros. The arrows indicate the direction of increasing space weathering. The presence of three different space weathering styles on the first three well characterized objects strongly implies that additional styles exist. Figure from [12]

Even for generally similar bodies such as Eros and Ida, significantly different space weathering effects are observed. Given, the compositional diversity of asteroids, it is likely that there are additional significant variations on the space weathering theme [e.g., 13, 14].

Space Weathering and Curve Matching: Direct curve matching involves comparison of a measured asteroid spectrum to a spectral library of potential samples or analogs, frequently with a space weathering correction applied. More complex curve matching procedures involve matching the unknown curve by a weighted average of the curves for a variety of potential components. This technique is routinely used to analyze thermal infrared spectra, but is less reliable for visible and near-infrared spectra. Some models have even incorporated a "space weathering" component into the mixing models. The existence of multiple styles of space weathering on asteroid surfaces presents a major complication to such approaches and significantly increases the ambiguity of any results.

Space Weathering and Spectral Parameters: Figure 2 shows the variation of Band I position versus space weathering index for sets of the lunar samples used to derive the $npFe^0$ lunar space weathering model.

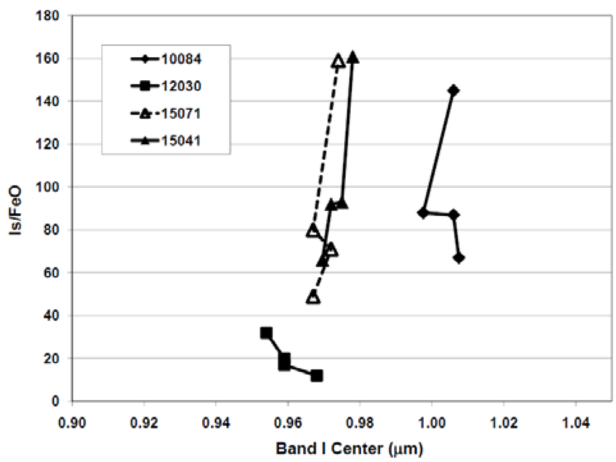

Figure 2 – Central wavelengths for Band I in the spectra of a subset of the lunar soil particle size separates described by [6]. Different size fractions of individual soils are joined by lines. The variation in band positions is very limited compared to the variations for the range of potential mineral compositions [12].

Up to high values of the space weathering index, there is no systematic effect of lunar style space weathering on the absorption band positions (centers). And modeling studies of asteroid space weathering [15-19] consistently show that until the mineralogy of the sample is seriously altered, the modeled space weathering does not significantly affect the diagnostic parameters of band centers or band area ratios. This work is summarized in [12].

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