SPACE WEATHERING: AN ULTRAVIOLET INDICATOR. A. R. Hendrix[1] and F. Vilas[2], [1]Jet Propulsion Laboratory/California Institute of Technology (amanda.hendrix@jpl.nasa.gov), [2]NASA Johnson Space Center.

Introduction: We present evidence suggesting that the spectral slope of airless bodies in the UV-visible wavelength range can be used as an indicator of exposure to space weathering. While space weathering generally produces a reddening of spectra in the visible-NIR spectral regions, it tends to result in a bluing of the UV-visible portion of the spectrum, and may in some cases produce a spectral reversal. The bluing effect may be detectable with smaller amounts of weathering than are necessary to detect the longer-wavelength weathering effects.

Effects of Space Weathering in the Visible/IR: Space weathering, the bombardment of airless bodies by micrometeoroids and irradiation by solar wind particles, affects solar system bodies by darkening and reddening their surfaces, as well as degrading absorption features [1], as seen at visible and near-infrared wavelengths. These effects, particularly in the visible and near-IR, are well documented for the Moon (e.g., [2]), where powdered rock samples are spectrally different from spectra of the lunar soil. The precise effect of weathering may be the vapor deposition, through solar wind irradiation and micrometeorite bombardment, of submicroscopic iron (SMFe) [3].

In the asteroid belt, fewer studies of space weathering effects have been performed than for the Moon. Recently weathering has been proposed as the source of spectral differences between ordinary chondrite (OC) meteorites and their proposed parent bodies, S-class asteroids [1][3]. The addition of nanophase Fe-bearing coatings to the grains of an OC meteorite sample results in spectral features similar to those of an S-type asteroid [3]. Although the solar wind flux is lower in the asteroid belt than at the Moon, less nanophase Fe is required to produce weathering effects on asteroids. Furthermore, on the S-type asteroid Ida Galileo SSI camera data indicate that a number of small, relatively fresh craters are blue compared with the reddish rest of the surface, using the 0.4/0.56 µm ratio, and exhibit stronger 1 µm absorption bands [4][1], effects that are consistent with lunar-like space weathering.

Effects of Space Weathering in the UV/Visible: Evidence indicates that effects of space weathering at UV-visible wavelengths include a bluing of the spectral reflectance and in some cases a spectral reversal. These effects are shown in analysis of lunar observations, laboratory spectra of lunar samples, UV data of Vesta, and laboratory space weathering experiments.

The Moon and Lunar Samples. Apollo 17 UVS measurements first displayed the lunar spectral reversal, where it was noted that the visibly dark lunar maria are 5-10% brighter than the highlands at far-UV wavelengths (147 nm) [5]; the phenomenon was also seen more recently in EUVE images [6]. The lunar spectral reversal was linked to space weathering when it was found that lunar soils exhibit the spectral reversal, while powdered lunar rocks do not [7], as shown in Fig.1. The lunar spectral reversal can be explained as being due to the higher index of refraction of mare material relative to highlands material [8]. The index of refraction of many materials increases with decreasing wavelength, so that they become brighter at shorter wavelengths. This is important because at shorter wavelengths, surface scattering dominates over volume scattering so that reflectance is directly related to the index of refraction [8]. However, the correlation between visibly bright and UV-dark lunar regions is imperfect, and UV spectra may therefore contain further information than what is known from visible spectra [8]. In particular, since far-UV radiation is less penetrating than visible radiation, short wavelengths are more sensitive to thin coatings on grains that may be the result of weathering processes [5].

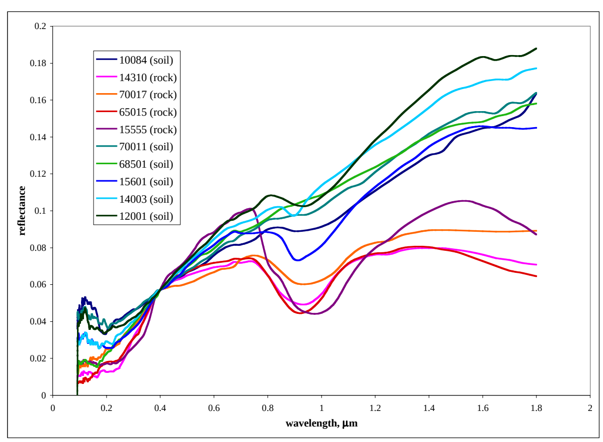

Fig. 1. Laboratory spectra of lunar soils and powdered rocks [7]. Spectra are scaled to the value of sample 10084 at 0.39 µm. The more-weathered lunar soils are redder in the visible-NIR, but bluer in the UV region shortward of ~0.4 µm, compared to the less-weathered powdered lunar rock samples.

Figure 1 displays the bluing phenomenon using UV-NIR spectra of lunar samples [7]. Lunar sample spectra that are redder at the longer visible-NIR wavelengths are actually bluer (less steep) at the shorter UV-visible wavelengths. This is evidence that the more-weathered lunar soils are redder at longer wavelengths *and* bluer at shorter wavelengths, than the less-weathered powdered lunar rocks. The lunar soils also display an upturn in brightness shortward of 0.2 μm, which corresponds to the spectral reversal.

Vesta. Ultraviolet spectra of Vesta display evidence of lunar-like ultraviolet space weathering on a global scale (compared with meteorite spectra) as well as in relative amounts across the surface. At UV-visible wavelengths, Vesta appears to be spectrally bluer than HED meteorites [9][10], particularly diogenite and eucrite samples. Because it is known that Vesta's visible-NIR spectra do not display strong lunar-like space weathering characteristics, this suggests that Vesta has undergone enough weathering to affect the blue part of the spectrum moderately, but not enough to strongly alter the visible-NIR spectrum.

Analysis of International Ultraviolet Explorer (IUE) data of Vesta [9] indicates that Vesta's UV lightcurve is offset by almost 180° from the visible lightcurve, meaning that this asteroid displays a spectral reversal. Regions on the surface that are relatively bright in the visible are relatively dark at NUV wavelengths. This suggests that Vesta's surface may have undergone varying amounts of space weathering. A global comparison between Vesta's topographic map and the IUE-derived lightcurve [9] suggests that the UV-dark region corresponds to the "fresher" overturned material related to the south-pole crater. Correspondingly, the UV-bright western hemisphere is dominated by a large region of average height, suggesting this region has not been affected by impact or accumulation of material after impact. This material is thus likely older than the exposed topographically low and high places, and may thus have experienced more weathering processes. Vesta's spectral reversal, and relative UV brightness of the older western hemisphere, may be due to the longer exposure time of this region, allowing it to accumulated more submicroscopic iron [3]. The spectral reversal could also be due to hemispherical compositional variations combined with the weathering process.

Experimental Laboratory Data. Laboratory experiments have demonstrated the sensitivity of the UV-visible wavelength region to simulated space weathering processes. The UV-visible wavelength region experiences drastic changes in brightness with very small amounts of weathering, as manifested by the addition of SMFe [3][10]. The addition of more SMFe through weathering flattens out the UV-visible portion of the spectrum; it becomes relatively blue. These laboratory results mimic the effects that are seen in lunar samples, where, shortward of ~400 nm, lunar soil has a bluer spectral shape compared to pulverized lunar rock [3] (also shown in Fig. 1). The lunar soil correspondingly is darker and exhibits attenuated absorption features at visible-near IR wavelengths, typical of weathering. Similar results are obtained in irradiation tests [3]: shortward of ~500 nm, the spectrum of an irradiated pulverized lunar rock is bluer (not as spectrally steep) than the unaltered pulverized lunar rock. Correspondingly, the irradiated sample is darker and exhibits subdued absorption features. Irradiation of a diogenite sample and a eucrite sample [11] have similar results as the lunar sample irradiation tests [3]. The irradiated meteorite sample is spectrally bluer shortward of ~500 nm than the unaltered sample, and has weaker absorption features and is somewhat redder at longer wavelengths.

These examples of the bluing of the UV-visible portion of the spectrum in response to simulated weathering are consistent with the UV spectral reversal: a sample that is more weathered will be spectrally bluer in the UV-visible region than a less weathered sample, and at some ultraviolet wavelength (likely composition dependent), the spectral reversal will occur. The result is that the more weathered sample, which is darker in the visible, ends up being brighter in the ultraviolet.

Further Evidence. To look for further evidence of space weathering effects in the UV, we investigate here asteroid data from Hubble Space Telescope (HST) and IUE, as well as from the Galileo Ultraviolet Spectrometer (UVS) and the Mariner 9 UVS. We compare the UV spectra with visible-IR wavelength spectra to look for changes in slope that are indicators of space weathering. We also compare the spacecraft data with the available laboratory data of meteorites.

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