ULTRAVIOLET EFFECTS OF SPACE WEATHERING ON THE MOON. A. R. Hendrix, 1 Jet Propulsion Laboratory/California Institute of Technology, 4800 Oak Grove Dr., MS 230-250, Pasadena, CA, 91109, hendrix@jpl.nasa.gov.

**Introduction:** Space weathering, the bombardment of airless bodies by micrometeoroids and irradiation by solar wind particles, profoundly affects the surfaces of airless bodies such as the Moon, impacting the compositional information that is obtained through remote sensing. The ultraviolet wavelength range is a particularly sensitive indicator of space weathering effects. Lunar soil samples and S-class asteroids are spectrally bluer at UV wavelengths than their less-weathered counterparts, crushed lunar rock samples and ordinary chondrite meteorites, respectively. In the NUV, this is due to the disappearance of the UV absorption edge as a result of weathering. This UV edge is present in nearly all materials and its strength is therefore an excellent indicator of exposure. The technique has been applied to lunar samples and UV data of asteroids [1][2]. Application to spectra of different terrains on the Moon will allow for the determination of relative ages of lunar terrains.

Silicate minerals are dominated at FUV wavelengths by an exiton/valence-conduction transition band system [3]; this band system makes silicates dark at FUV wavelengths, while the NUV region is dominated by a decrease in reflectance with wavelength – I refer to this as the “UV dropoff,” or the “UV absorption edge.” Figure 1 displays spectra of various silicate materials, which demonstrate this UV dropoff. Reflectance spectra at visible – near-infrared (VNIR) wavelengths are controlled predominantly by volume scattering [4][5], where the intensity of the reflected light is inversely proportional to wavelength. At shorter wavelengths, a transition to surface scattering occurs; the intensity of surface scattering is proportional to the Fresnel reflection coefficient: 
\[
R \sim \left( \frac{n}{n-1} \right)^2 + k^2 \left( \frac{n+1}{n-1} \right)^2,
\]
In non-opaque materials, the transition to surface scattering occurs in the 150-450 nm region [5] and is marked by a minimum in reflectance. Opaque materials (such as iron) are dominated by surface scattering, and are thus spectrally flat over a wide range of wavelengths; in opaques, there is no absorption edge in the 150-450 nm region. Thus, compared to materials such as pyroxenes and feldspars, iron-bearing minerals can be relatively bright at UV wavelengths. In the 150-450 nm range, iron-bearing minerals also differ from non-opaques in spectral shape, where the non-opaques experience a decrease in brightness as they transition from reflectance dominated by volume scattering to reflectance dominated by surface scattering and opaques tend to be spectrally flat. Such spectral trends have been used to map FeO and TiO₂ abundances on the Moon and Mercury (e.g., [6][7][8][9]), generally employing and comparing data in orange (575 nm) and UV (375 nm) filters; here we focus on spectral data, extending to even shorter wavelengths.

![Figure 1. Reflectance spectra of various minerals and meteorites at UV-NIR wavelengths (after [5]; data used with permission of J. Wagner). Pyroxenes, feldspars, olivines, and chondritic meteorites all exhibit a UV dropoff in the 150-450 nm range that is not seen in iron-bearing minerals (ilmenite, magnetite) [2].](Image 333x510 to 525x625)

**Previous Results:** At VNIR wavelengths, space weathering affects spectra of solar system bodies by darkening and ‘reddening’ (where the spectral reflectance increases with wavelength) their surface materials, as well as degrading absorption features [10]. A primary effect of space weathering at VNIR wavelengths is the degradation of absorption features such as the 0.9 µm pyroxene band. These effects are well documented for the Moon (e.g.,[11]), where they are apparent in spectra of natural lunar soils, but not seen in spectra of powdered lunar rock samples. The cause of these weathering effects is likely vapor deposition of submicroscopic iron (SMFe) [12][3], through solar wind irradiation and micrometeorite bombardment of the bodies’ surfaces.

![Laboratory spectra of lunar samples in the UV-IR wavelength ranges (from [5]) are shown in Figure 2. Longward of ~0.6 µm, lunar soils are clearly redder (and darker) than crushed lunar rocks. At ultraviolet wavelengths, the opposite is true: in this range, lunar rocks are spectrally redder than lunar soils.](Image 2151.pdf)
the reflectance data in each wavelength range [2]. The trend is obvious: the less-weathered crushed lunar rocks have lower (less red) VNIR slopes and higher (redder) NUV slopes, while the more-weathered lunar soils have higher (redder) VNIR slopes and lower (bluer) UV slopes. Figures 2 and 3 demonstrate the significance of the UV wavelength region in reflecting space weathering effects.

**Figure 2.** Laboratory spectra of lunar soils (thick lines) and powdered rocks (thin lines) (from [5]). Left panel: Spectra are scaled to unity at 0.57 µm to enhance variations in slopes. Right panel: Spectra are plotted on absolute scale to display relative brightness variations. The more-weathered lunar soils are redder in the VNIR, but bluer in the UV region shortward of ~0.4 µm, compared to the less-weathered powdered lunar rock samples. From [2].

**LRO/LAMP Investigation:** Complete maps of the Moon in the 100-190 nm range from LRO/LAMP [13] will allow for compositional measurements, as well as the measurement of varying amounts of space weathering across the surface and will help to establish relative ages of terrain types. We plan to map FUV spectral slopes across the lunar surface, to determine relative exposure ages of each region. As previously shown, regions that are spectrally blue in the FUV are predicted to be older, more weathered regions than areas that are relatively spectrally red. An example is shown in Figure 4, where lunar soil samples are spectrally bluer in the LAMP wavelength range than crushed lunar rocks. Lunar soils experienced greater exposure on the lunar surface and are thus more weathered than the lunar rocks. The relatively unweathered lunar rocks are spectrally flat or reddish in this wavelength range. Once the lunar surface is mapped by LAMP, FUV images can be compared and cross-correlated with images to compare with surface feature such as cratering amounts and crater rays that may be fresher and less weathered. Implications include detection of regions of lower amounts of radiation (perhaps due topographic shielding), which could be suitable for future landing sites.

**Figure 3.** Spectral slopes (in units of reflectance/nm) of lunar samples showing trends with weathering. Lunar soils are redder at VNIR wavelengths and bluer in the UV while the opposite is true for lunar rocks. From [2]. A similar relationship has been found for S-class asteroids and ordinary chondrite meteorites [2].

**Figure 4.** Lunar soils (relatively weathered) and crushed rocks (relatively unweathered) in the FUV (from [5]). Soils are spectrally bluer than rocks in the FUV.