**ULTRAVIOLET SPECTROSCOPY OF THE MOON: CLUES ABOUT COMPOSITION AND WEATHERING.**
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**Introduction:** The canonical method for investigating the surface composition of planetary surfaces is near-infrared spectroscopy. Ultraviolet measurements of the lunar surface exist and represent an exciting opportunity to do UV lunar mapping and mineralogy, potentially yielding unique information that is complementary to data obtained at VNIR wavelengths.

In this project to study the Moon we utilize the ultraviolet wavelength range, which has been shown to be sensitive to weathering effects and also contains diagnostic compositional features. We focus on lunar observations from the International Ultraviolet Explorer (IUE) and the Galileo Ultraviolet Spectrometer (UVS). We concentrate on these datasets because of the unique information that can be gleaned by studying UV spectra, and because the IUE dataset is vast -- yet has been largely unanalyzed. Furthermore, these data provide an excellent basis with which to compare and put into context the new UV data from the Lunar Reconnaissance Orbiter's Lyman Alpha Mapping Spectrometer (LRO/LAMP).

**Background:** Many species exhibit UV absorption edges, often due to the $Fe^{3+}$ intervalence charge-transfer transition band seen in almost all iron-bearing silicate surfaces, in the NUV. Silicate minerals are dominated by an exciton/valence-conduction transition band system below 200 nm [3][5][14]; they are bright in the VNIR, but the wings of the band system make the minerals start to decrease in brightness in the NUV - referred to here 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: $R \sim [(n-1)^2 + k^2]/[(n+1)^2 + k^2]$. 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 $TiO_2$ 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.

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 can allow for the determination of relative ages of lunar terrains.

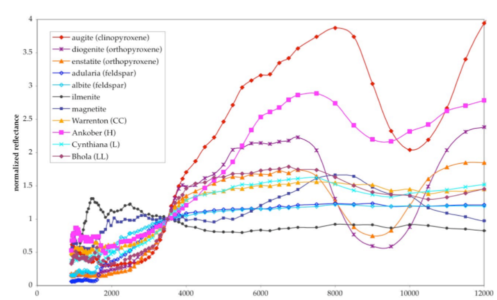


**Figure 1.** Reflectance spectra of various minerals and meteorites at UV-NIR wavelengths (after [5]; data used with permission of J. Wagner). Pyroxenes, feldspars, olivines, and chondritic meteorites all exhibit a UV dropoff in the 150-450 nm range that is not seen in iron-bearing minerals (ilmenite,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

**Space Weathering Effects:** 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. The lunar rocks display a steep UV drop-off that is greatly reduced in the lunar soils. Additionally, shortward of 0.2 µm, the lunar soils' spectra tend to display an upturn in brightness, which corresponds to the spectral reversal (discussed in the previous section). 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, demonstrating the significance of the UV wavelength region in reflecting space weathering effects.

**This Study:** In this project, we create a composite UV dataset of the Moon to study spatial variations that are the result of compositional and weathering effects. We concentrate on data from IUE and Galileo and include comparisons with new data from LRO/LAMP as possible. We focus on the extensive IUE database (on the order of 200) of lunar observations, whch has been largely uninvestigated and unpublished. We combine the IUE dataset with Galileo UVS measurements of the Moon to increase the coverage of the UV database. The Galileo UVS observations were taken using the UVS F-channel (162-323 nm, with a 0.32 nm spectral element spacing). IUE spectra were taken with the Long Wavelength Prime and Redundant (LWP and LWR) spectrographs that cover the 185-335 nm wavelength range with a spectral spacing of 0.27 nm. The low resolution channel has a spectral resolution of 7-8 Å FWHM; the high resolution mode gives a spectral resolution in the range 0.1-0.2 Å FWHM. The Short Wavelength Prime (SWP) spectrograph covers the 1150-1975 Å wavelength range.

LRO has been in orbit since July 2009 and LAMP has been taking data of the lunar dayside since October. Eventually, 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 present lunar spectra covering the far-UV through mid-UV wavelength range (~110-330 nm) to investigate compositional and weathering variations as related to surface features, including new data from LRO/LAMP as feasible.

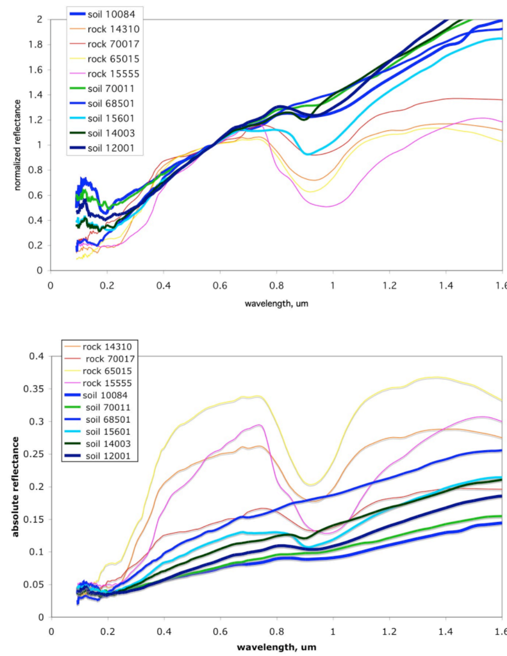


**Figure 2**. Laboratory spectra of lunar soils (thick lines) and powdered rocks (thin lines) (from [5]). Upper panel: Spectra are scaled to unity at 0.57 µm to enhance variations in slopes. Lower panel: Spectra are plotted on absolute scale to display relative brightness variations. The more-weathered 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].

**References:** [1] Hendrix, A. R. et al. (2003) *Icarus, 162, 1.* [2] Hendrix, A. R. & Vilas, F. (2006) *AJ, 132,* 1396. [3] Hapke, B. (2001) *JGR, 106,* 10039. [4] Hapke, B. et al. (1981) *Icarus, 47,* 361. [5] Wagner, J. et al. (1987) *Icarus, 69,* 14. [6] Rava, B. and Hapke, B. (1987) *Icarus, 71,* 397. [7] Robinson, M. & Lucey, P. (1997) *Science, 275,* 197. [8] Lucey, P. et al. (1998) *JGR, 103,* 3679. [9] Robinson, M. & Taylor, L. (2001). *MSP, 36,* 841. [10] Chapman, C. (1996) *MPS, 31,* 699. [11] Pieters, C. et al. (1993) *JGR, 98,* 20817. [12] Pieters, C. et al. (2000) *MPS, 35,* 1101. [13] Gladstone, R. et al. (2005). *SPIE, 5906.* [14] Smith, D. Y. et al. (2005) *Phys. Stat. Sol., 2,* 310.