ULTRAVIOLET SPECTROSCOPY OF THE MOON: A NEW LOOK AT SOME NOT-SO-NEW DATA SETS.

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Introduction: Ultraviolet measurements of the lunar surface represent an exciting opportunity to do UV lunar mapping and mineralogy, potentially yielding unique information that is complementary to data obtained at VNIR (visible-near infrared) wavelengths.

In this project to study the Moon we utilize the ultraviolet wavelength range, which has been shown to be sensitive to space weathering effects and also contains diagnostic compositional features. We tap into data sets that have been not exploited fully so far: observations from the International Ultraviolet Explorer (IUE), the Galileo Ultraviolet Spectrometer (UVS), the Cassini Ultraviolet Imaging Spectrograph (UVIS) and the Apollo 17 UVS. 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).

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 [1][2]. 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.

Data Sets: 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. In this project, we create a composite UV dataset of the Moon, which will ultimately be available to the public, to study spatial variations that are the result of compositional and weathering effects. We concentrate on data from IUE (far-UV and near-UV) and Galileo (near-UV) and include data from Cassini UVIS (far-UV) and Apollo 17 UVS (far-UV).

The Apollo 17 UVS observations of the surface cover the ~120-170 nm range. A single-wavelength scan of the surface was published [3] which was used to derive a photometric function and also showed important albedo variations with terrain type (discussed further below); an FUV lunar reflectance spectrum was also published. However, the entire data set has not been fully studied or published so far. We will present these data.

The Galileo UVS observations were taken using the UVS F-channel (162-323 nm, with a 0.32 nm spectral element spacing) of regions (often roughly 200x800 km in extent) scattered across the lunar surface during the two Earth-Moon flybys in 1990 and 1992 [4].

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. The IUE observations cover various regions across the near side the Moon.

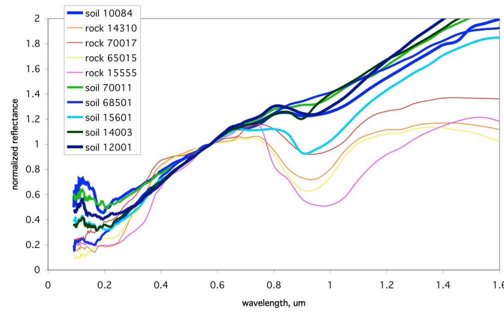
The Cassini UVIS made a single observation of the Moon during the Earth-Moon flyby on August 18, 1999. The observation covers the ~110-196 nm spectral range. The solar phase angle during the observation was ~90°; the terminator was located at ~345°W. The observation was designed such that the UVIS slit was oriented along the equator of the Moon and pointed at a fixed RA/Dec; the Moon moved along the length of the UVIS slit. As the Moon moved through the UVIS slit, signal was recorded first from the illuminated half of the disk, then the night-side. As a result of the observational style, the spatial resolution during the observation is low, but the data are useful nevertheless.

UV Compositional Effects: 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 [5][6][9]; they are bright in the VNIR, but the wings of the band system make the minerals start to decrease in brightness in the NUV. Reflectance spectra at visible – near-infrared (VNIR) wavelengths are controlled predominantly by volume scattering [12][6], 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 [6] 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.

UV Space Weathering Effects: 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. At VNIR wavelengths, space weathering processes affect 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 [7]. The cause of these weathering effects is likely vapor deposition of submicroscopic iron (SMFe) [5][8], through solar wind irradiation and micrometeoroid bombardment of the bodies' surfaces.

Laboratory spectra of lunar samples in the UV-IR wavelength ranges (from [6]) are shown in Figure 1. 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 (a decrease in albedo that occurs generally between 200 and 500 nm) 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 more later). Figure 1 demonstrates the significance of the UV wavelength region in reflecting space weathering effects.

Furthermore, ultraviolet measurements of the Moon from space have also suggested space weathering effects. 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) [10]. The lunar spectral reversal was linked to space weathering when it was found that lunar soils, which have been exposed to more weathering, exhibit the spectral reversal, while powdered lunar rocks do not [6]. The lunar spectral reversal is due in part to the higher index of refraction of mare material relative to highlands material [11]. At shorter wavelengths, surface scattering dominates over volume scattering so that reflectance is directly related to the index of refraction [11]. The index of refraction of many materials increases with decreasing wavelength, so that they become brighter at shorter wavelengths. However, the correlation between visibly bright and UV-dark lunar regions as seen by Apollo 17 is imperfect, and UV spectra may therefore contain more information than what is known from visible spectra [11]. 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 [10].



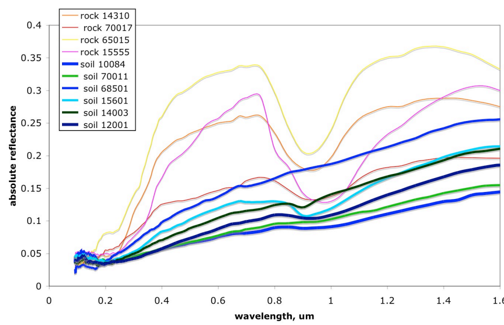


Figure 1. Laboratory spectra of lunar soils (thick lines) and powdered rocks (thin lines) (from [6]). Upper panel: Spectra are scaled to unity at 0.57 μm to enhance variations in slopes. Lower panel: Spectra are plotted on absolute scale to display relative brightness variations. The more-weathered lunar 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].

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