Testing the relation between UVVIS color and TiO$_2$ composition in the Lunar Maria. J. J. Gillis, P. G. Lucey, and S. J. Lawrence, University of Hawai‘i at Manoa, Hawai‘i Institute of Geophysics and Planetology, 1680 East-West Road, POST 504, Honolulu, HI 96822 (gillis@higp.hawaii.edu).

**Introduction:** This study addresses the degree of correlation between Ti and UVVIS color via a focused examination of lunar soils and a quantitative understanding of their optical properties and the optical properties of their components. It is clear that lunar basalts show strong and consistent variations in UVVIS color that certainly can be used for mapping flow boundaries; but to what extent these variations in any individual mare deposit are dependent upon Ti or other compositional parameters is not well established. Opaque minerals certainly must at least contribute to lunar UVVIS color as they vary from 0 to almost 25% by volume [1]. As suggested by Staid et al [2], soil mineralogy is a factor influencing spectral variation. Thus, we test the relation between UVVIS color and various factors that include mineralogy and mineral chemistry. Improving the correlation between these two parameters will result in increasing the accuracy of TiO$_2$ estimated using remotely sensed data.

**Background:** Isolated color variations observed between ultraviolet and visible wavelengths in the maria denote relative differences in spectral reflectivity. A steep UVVIS continuum is termed “red” and flatter UVVIS continuum is termed “blue”. A relation between Laboratory UV/VIS spectra and TiO$_2$ composition of Apollo and Luna bulk regolith samples was describe empirically and demonstrated applicable to remotely sensed data [3]. The Charette relation provided the capability to quantitatively estimate mare composition on the basis of 400/560 nm ratio of mature (agglutinate rich) mare surfaces. Uncertainties in the method were revealed with failure to accurately predict the low-Ti contents of the Luna 24 basalts. Remotely sensed data estimated that Mare Crisium contained 3-4 wt.% TiO$_2$ [4] but analysis of Lunar 24 samples indicated that they contain <1 wt.% TiO$_2$ [5,6]. Subsequent revisions were made to account for uncertainties at low TiO$_2$ concentrations [7].

The recent Clementine [8], and Lunar Prospector [9] Missions have brought about a renaissance in mapping TiO$_2$ composition. The Lunar Prospector Mission has provided us with global ground-truth data with which to test the correlation between TiO$_2$ content and UVVIS slope. A comparison of Clementine spectral reflectance (CSR) data and Lunar Prospector neutron spectrometer (LP-NS) data for TiO$_2$ [10] illustrates the poor correlation between these two parameters (Fig 1). For instance, a UV/VIS value of 0.6 would represent TiO$_2$ values between 0 and 5 wt% (equivalent to 2±2 wt%). This poor correlation between UVVIS color and TiO$_2$ content of lunar basalts has thus far not been explained.

A comparison between neutron TiO$_2$ and Clementine UVVIS, scaled to similar 2-degree resolution, show that while a positive correlation exists between the two data sets, the ability to accurately predict TiO$_2$ concentration from a UV/VIS value is poor. For example, a UV/VIS value of 0.6 could represent TiO$_2$ values in the range of 0 to 4 wt.% TiO$_2$. A better accuracy is desired as it is important to differentiate between basalts with very low (<1 wt.) compositions of TiO$_2$ and those of low and moderate TiO$_2$ concentrations. Thus, we investigate the causes of color in order to identify possible factors other than ilmenite concentration that have an affect on UVVIS color.

**Data & Methods:** The Clementine Mission acquired multispectral data (415, 750, 900, 950, 1000 nm) at unprecedented resolution (~200 m/pixel). The Lunar Prospector gamma-ray and neutron spectrometer data collected data for TiO$_2$ at 60 km/pixel resolution. The data presented here are all resampled to 2°/pixel resolution between latitudes -70 to 70. We also use Hapke modelling to characterize the reflectance spectra of various minerals.

Factors other than ilmenite that we suspect may contribute to the poor correlation between UVVIS color and TiO$_2$ composition are: 1) Ti contained in silicates instead of ilmenite; 2) Non Ti-bearing opaque phases; 3) Iron content of silicates; 4) Modal
abundance of Olivine; and 5) Trace element content of silicates

Each of these factors has the potential affect on the reflectance properties of lunar materials. Small amounts of Ti can be accompanied in pyroxene, as in the case of Apollo 11. This substitution of Ti into the pyroxene lattice causes the mineral to acquire a pink hue; thus, changing its inherent color. The presence of Ti-free opaques, such as chromite or spinel, would obviously contribute to poor correlations between UV/VIS color and Ti. The iron content of silicate minerals in basalts and soil glass has a strong control on the visible reflectance that can also contribute to variations in UV-visible ratio. Finally, trace or major elements can also have strong effects on visible color in many minerals, so these phenomena could also contribute to poor correlations between Ti and lunar color.

Results & Discussion: We investigate Mare Crisium as a ground-truth point because it lies off the trend defined by the Charette relation and we have sample information. Soils from Lunar 24 contain fragments of ferrobasalt and ferrogabbro. The ferrobasalt is very low TiO$_2$ (<1wt%), relatively high Al$_2$O$_3$ (12-14wt%), and unusually low Cr$_2$O$_3$ relative to other mare basalts in the sample collection [6]. Samples from Mare Crisium also exhibit the highest FeO values of any basalt in the lunar sample collection, at 20.5 wt%.

The petrology and mineral chemistry of the samples is also distinct. The modal abundances of opaques, feldspar, and olivine in Luna 24 samples are different compared with other basalt samples. For instance, the Luna 24 basalts contain the second lowest modal percentage of opaques of basaltic samples in the lunar collection (1.8%), which is far lower than the basalt types used to calibrate TiO$_2$ algorithms. Apollo 17 very high Ti contains 24.4% opaques and Apollo 11 low-K has 14.6%; the lowest modes are Apollo 15 olivine and pigeonite basalts, which contain 5.5 and 3.7% opaques respectively [6]. Another difference petrologically is the modal abundance of olivine in the Luna 24 samples (10.4%), second only to the Apollo 12 olivine basalts with 20.2% olivine [6]. Apollo 17 contains, at most, 4.6% olivine and Apollo 15 olivine basalts contain 7%. In addition, the Luna 24 olivines are zoned to much more Fe-rich compositions (Fos0$_7$-Fo$_{49}$) than the olivine of Apollo 17 VLT basalt (Fos$_{99}$-Fo$_{49}$). Pyroxenes also exhibit similar iron-rich compositions (Fs$_{99}$-Fs$_{99}$). This suggests that either the high modal percentage of olivine or the high FeO composition of the olivine and pyroxene within these basalts may be contributing to UV/VIS continuum.

Hapke modeling of mineral spectra demonstrates the dramatic affect increased iron has on reflectance spectrum of pyroxene and olivine (Fig. 2). As illustrated, increasing iron concentrations from an Mg#99 to an Mg#1 lowers reflectance values for the wavelengths modeled (0.8–2.3 μm). While these data do not include the UV portion of the spectrum, studies of lunar soil reflectance values have established that lunar soils exhibit low spectral contrast in the UV portion spectrum. Therefore, it is plausible that reduction in reflectance in the near infrared, caused by increased iron in silicates, coupled with the inherently low spectral contrast of lunar soils at UV wavelengths yields a flatter UV/VIS continuum. This effect is also observed in Clementine spectra of mare basalts with >20 wt% FeO and <4 wt% TiO$_2$. In these instances the high FeO basalts exhibit bluer spectra than lower FeO basalt with similar TiO$_2$ concentrations.

Fig2. Reflectance values modeled using Hapke theory for high iron (Mg# = 1) and low iron (Mg# = 99) olivine and pyroxene phases (grain size 25μm). Mg# = atomic Mg/[Mg+Fe]

Conclusions: Variations in FeO content of silicates appear to affect UV/VIS color by disproportionately lowering reflectance at 750 nm relative to 415 nm; hence lowering the correlation between UV/VIS ratio and TiO$_2$ content of mare basalts. Factors such as Ti content of silicates and presence of non Ti-bearing opaque phases appear to have less of an affect on UV/VIS color but this still needs to be rigorously tested using additional sample data.