OPTICAL PROPERTIES OF THE FINEST FRACTION OF LUNAR SOIL: IMPLICATIONS FOR SPACE WEATHERING ENVIRONMENTS. S. K. Noble[1], C. M. Pieters[1], L. A. Taylor[2], R. V. Morris[3], C. C. Allen[4], D. S. McKay[3], L. P. Keller[5], [1]Brown University, Providence, RI 02912, noble@porter.geo.brown.edu, [2]Univ. of Tenn., Knoxville, TN 37996, [3]NASA JSC, Houston, TX 77058, [4]Lockheed Martin, 2400 NASA Road 1, Houston, TX 77058, [5]MVA Inc., 5500/200 Oakbrook Parkway, Norcross GA 30093.

Introduction: The optical properties of the bulk are most similar to the finer fractions of lunar soils (10-45µm) [1]. Because these bulk properties are skewed towards the smaller fractions, it is very important to understand how the character of the soil changes as we look at smaller particles. The finest fraction of lunar soils (defined here as <10µm) is geochemically and petrologically different from larger size fractions. It is enriched in felspathic components [2] and agglutinitic glass [3], as well as other weathering products relative to larger size fractions. We show that the spectral character of this finest fraction is controlled by trends in both composition and maturity, which ultimately are linked to the amount of nanophase Fe produced in the weathering process.

Data Set: Several studies of the optical properties of lunar materials have been carried out using particle size separates of lunar soils. Table 1 lists the <10µm size fraction soil samples available for this study. The freon sieved highland samples were measured for Fischer [4] to represent soils of different maturity but similar composition. The dry sieved samples were originally measured for phase 1 of the lunar soil characterization consortium [5] and the water sieved samples are from phase 2 [6]. These mare soils were chosen to represent a large variety of both composition and maturity. The spectral properties of these samples are summarized in figure 1. Where both a wet and dry sieved sample have been measured, only the wet sieved is shown.

Sample #	I_s/FeO <250µm	Dry Sieved[5] <10µm I_s/FeO	Freon Sieved[4] <10µm I_s/FeO	Water Sieved[3] <10µm I_s/FeO
10084	78	137#		145
12001	56			115
12030	14	37#		32
15071	52			159
15041	94			161
61221	9		36	
64801	71		145	
67701	39		81	
68501	85	X(by hand)*		
70181	47	X		104
71501	35			88
71061	14			28
79221	81	167#		169

Table 1. I_s/FeO of bulk and <10µm samples of lunar soils. X indicates soils for which data are not yet available. *measured for this study. #assuming FeO from water sieved samples.

Compositional Trends: From Fig. 1, it can be seen that the finest fraction of highland soils have very different spectral properties than mare soils. The continuum of the finest fraction of feldspathic soils increases in the visible, then flattens at longer wavelengths [8], while the continuum of the finest fraction of basaltic soils continues to increase in a steep, almost linear fashion throughout the Vis-NIR [6]. While preparation methods (the use of freon or dry sieving) do have minor effect on the spectral properties of this finest fraction [9], they cannot account for this difference between the finest fraction of mare and highland. Thus, we believe that these continuum differences are real and directly related to the compositional differences between the Fe-rich mare and the feldspathic highlands.

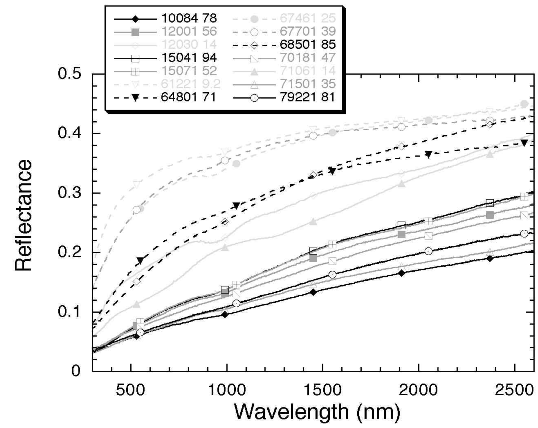

Figure 1. Bi-directional reflectance spectra of the <10µm samples used in this study. Solid lines are mare, dotted are highlands. Light gray represent immature soils, dark gray = submature, and black = mature. The bulk soil I_s/FeO values are given in the legend.

Maturity Trends: Space weathering causes systematic changes in the optical properties of lunar soil over time. With increasing maturity, it has been found that lunar soil spectra typically become darker, more red, and lose their spectral contrast. The finest fraction are no exception. Preliminary results show systematic variations between the <10µm finest fraction of soils of varying exposure ages (maturity) as measured by I_s/FeO. The mature samples of both mare and highlands are darker than their immature counterparts. Also, more mature soils exhibit a greater loss of spectral contrast such that in the finest fraction, absorption bands have all but disappeared.

From figure 1 it is clear that the immature and submature highland samples (61221, 67701, 67461) show the most dramatic turn-over and flattening at longer wavelengths. The mature highland samples (64801, 68501) show significantly steeper slopes than their less mature relatives. It appears that as the highlands weather, their continuum slopes become increasingly linear and more red. In contrast, it is the two immature mare soils (12030, 70161) that stand out from their more mature counterparts. This is due to their brightness and distinct absorption bands, but also because the other mare soils all tend to converge in the visible while the immature soils are significantly brighter even at those wavelengths. Additionally, if the strong absorption bands are ignored, the continuums of 12030 and 70161 are quite similar in character to the mature highland samples, displaying a slight, but noticeable, curvature. In contrast to the highland soils, both the submature and the mature mare soils exhibit flatter (less red) continua than the immature samples.

Explanation for compositional differences: Nanophase Fe is the term given to very tiny inclusions (40-330Å in dia [10]) of Fe^0 created in the space weathering process. Much of this nanophase Fe resides in thin rims surrounding individual soil grains [11] and has a large influence on the spectral character of the soil. Mare soils have at least three times the total FeO content of highland soils. The more Fe available in the soil, the better the opportunity of creating nanophase iron, so we expect the I_s values, which are a measure of the amount of nanophase Fe [7] of mare soils to be significantly higher than highlands.

In order to evaluate the optical effects of varying amounts of nanophase Fe^0, Allen et al [12] has performed experiments using silica gel powders (35-74µm) with nanophase Fe as an optical analog for lunar soils. Their results in figure 2 indicate that samples with very small wt% Fe (<2 wt%) show significant red slopes. Of particular interest is the 0.2 wt% Fe spectrum, the smallest amount of Fe tested. The continuum of this sample exhibits a steep curvature in the visible and flattening at longer wavelengths that is very similar in shape to the <10µm highland samples. The 0.47 wt% Fe sample of Allen's analog is similar in shape to our reddest samples, the immature mare and mature highland. Subsequent analog samples with larger wt% Fe begin to lose redness as their whole spectrum becomes darker, eventually resulting in a flat and featureless continuum.

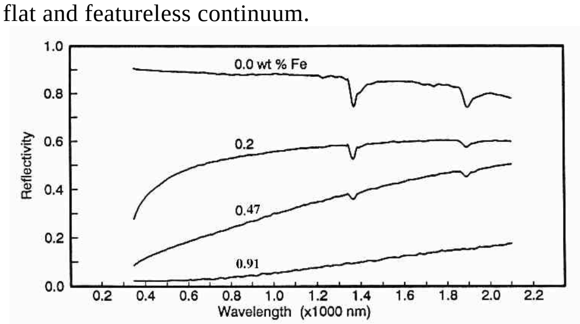

Figure 2. Results of Allen's lunar soil analog for various wt% Fe implaced in silica gel particles [12].

In figure 3, data from Morris [10] are plotted to show the relationship between I_s and the wt% metallic iron created by the exposure-induced reduction of ferrous iron. As expected, this is a linear relationship. The I_s values of our <10µm samples are indicated with arrows. The finest fraction have higher values of I_s due to the greater concentration of weathering products. From this line we can extrapolate the wt% Fe^0 for our samples. These wt%s are somewhat smaller than the values for the experimental analogs with similar continuum shapes, but the relationship between amount of Fe^0 and spectral shape is the same.

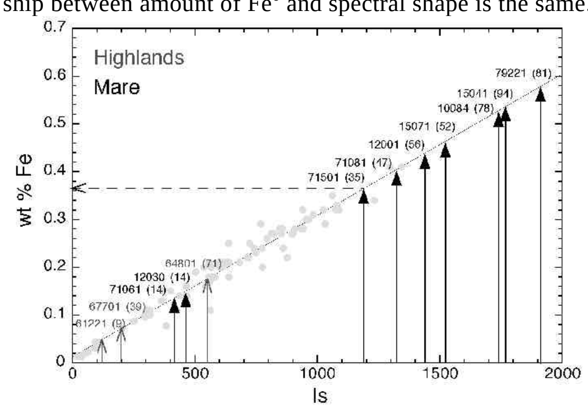

Figure 3. Relation between Is and Wt% Fe derived from lunar soils [morris ref]. The arrows show the <10µm I_s values which can then be extrapolated in order to obtain estimates for the weight percent of nanophase Fe present in each sample. Solid arrows indicate mare samples, open arrows represent highlands. The soils are labeled with their sample number followed by their bulk soil I_s/FeO value.

The curvature of the spectrum due to very small amounts of nanophase Fe is something that is seen only in the finest fraction and Allen's experimental analog which used 35-74µm size particles. This is a function of the amount of light that is transmitted through a grain. It appears complex lunar soil particles need to be <10µm before they are transparent enough to see this effect. The experimental analog used transparent silica gels, and therefore, the effect was detectable even in much larger size particles.

Conclusions: We find that the optical properties of the finest fraction of lunar soils are controlled by a combination of effects due to maturity and composition. The more a soil has been exposed at the surface, the more time it has to accumulate weathering products and thus the optical effects of weathering are strongest in the most mature soils. Comparing immature samples of finest fraction to more mature samples reveal clear trends; as maturity increases the soils become generally darker and lose their spectral contrast.

For transparent or semi-transparent materials the amount of nanophase Fe is very important in determining the shape of the continuum. In the finest fraction of lunar soils the process can be broken into four stages: (1) Small amounts of nanophase Fe results in a prominent curvature in visible wavelengths, while leaving the longer wavelengths largely unaffected. (2) As nanophase Fe accumulates, the continuum becomes less curved and more red, reaching a peak redness between 0.15 and 0.35 wt% Fe^0. (3) Additional nanophase Fe results in an increasingly linear continuum that starts to lose redness (4) Following the trend of Allen's analog, if significantly more nanophase Fe could be added to the soil, we would expect that eventually, the continuum would become dark and featureless. However, even our most mature Fe-rich (mare) sample still has a significantly red slope. The natural soils seem to find an equilibrium state where the creation and destruction of weathered rims and the influx of new material balance. Mature mare soils end at stage 3. Mature highland soils, having less iron available, only reach stage 2.

The invaluable information provided by returned lunar soils is the only ground-truth currently available for understanding airless bodies. Factors controlling the development and abundance of nanophase Fe and overall transparency of soil particles are key properties affecting the products of space weathering observed for regoliths in other environments, i.e. asteroids and Mercury.

References: [1] Pieters et al (1993) [2] Papike J.J. et al (1981) PLPSC12th p.409-420. [3] Taylor L.A. et al (1999) LPSCXXX #1885. [4] Fischer E.M. (1995) Ph.D. thesis, Brown Univ. [5] Taylor L.A. et al (1997) LPSCXXIX, #1160. [6] Pieters C.M. et al, this vol. [7] Morris R.V, (1977) 8thPLPSC, 3719-3747. [8] Fischer E.M. et al (1994) LPSCXXV, 371-372. [9] Noble S.K. et al (1999) LPSCXXX #1669. [10] Morris R.V. (1980) 11thPLPSC, 1697-1712. [11] Keller L.S. et al (1998) LPSCXXIX #1762. [12] Allen C.C. et al (1995) LPSCXXVII, 13-14.

Acknowledgements: RELAB is supported as a multi-user facility under NASA grant NAG5-3871. The skilled assistance by Takahiro Hiroi in obtaining spectra is greatly appreciated. NASA support (NAG5-4303) is gratefully acknowledged.