

**THE SPECTRAL PROPERTIES OF LUNAR AGGLUTINATES.** Brett W. Denevi<sup>1</sup>, Chanud N. Yasanayake<sup>1,2</sup>, Bradley L. Jolliff<sup>3</sup>, Samuel J. Lawrence<sup>4</sup>, Takahiro Hiroi<sup>5</sup>, and Anna C. Martin<sup>1</sup>, <sup>1</sup>Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA, <sup>2</sup>Johns Hopkins University, Baltimore, MD 21218, USA, <sup>3</sup>Washington University in St. Louis, St. Louis, MO 63130, USA, <sup>4</sup>NASA Johnson Space Center, Houston, TX 77058, USA, <sup>5</sup>Brown University, Providence, RI 02912, USA.

**Introduction:** Agglutinates comprise a large fraction of mature lunar soils, and form when micrometeoroid impacts produce glass that welds together other soil particles. This process results in intricate, vesicular, and irregularly shaped particles that are typically brown in color. The dark color of agglutinates is related in part to the small (nm– $\mu$ m scale) particles of iron contained within the impact glass; this iron is incorporated into agglutinitic glass either via reduction of iron-bearing minerals during the melting process, or through remelting of previously weathered iron-metal-bearing soil components [e.g., 1–3].

In spite of their abundance in the regolith and significance for space weathering, the spectroscopy of agglutinate separates has only infrequently been the focus of research [e.g., 4,5]. Here we present results from the spectral characterization of agglutinates separated from six Apollo soil samples of varying composition and maturity (Table 1).

**Table 1.** Characteristics of Apollo samples used in this study.

Sample	FeO (wt%)	TiO <sub>2</sub> (wt%)	Maturity (I <sub>s</sub> /FeO)
14259	9.5	1.8	Mature (85)
15041	14.2	1.8	Mature (94)
61141	5.3	0.6	Submature (56)
62231	4.9	0.6	Mature (91)
67461	4.2	0.3	Immature (25)
79221	14.0	6.4	Mature (81)

**Agglutinate Separation:** We tested two methods to separate agglutinates from the 125–250  $\mu$ m fraction of our samples. In the first method, soil particles were examined under a binocular microscope, and agglutinates were identified based on their distinct appearance (irregular shape, typically brown in color, surface texture varying from rough to glassy, inclusions of mineral fragments), and manually separated with tweezers.

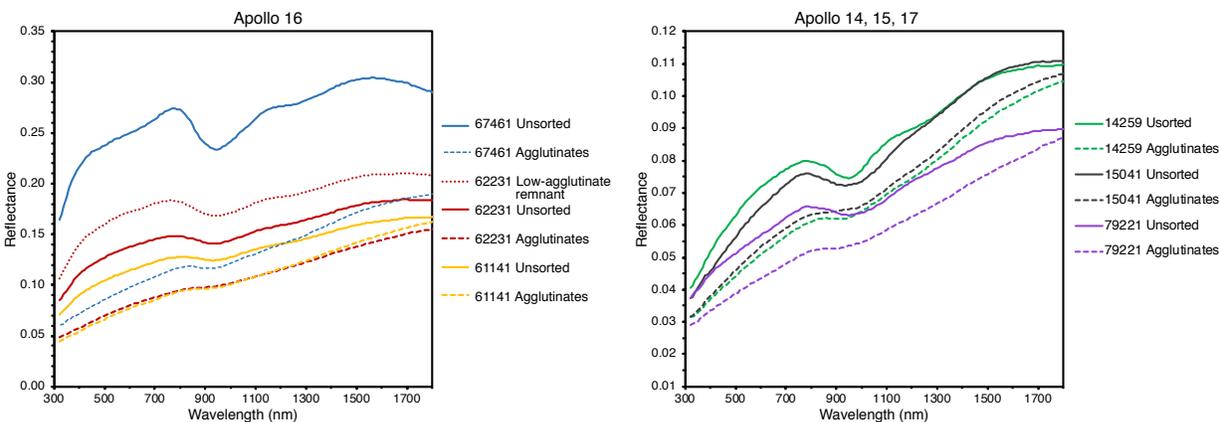
In the second method, the soil was magnetically sorted using a Frantz magnetic separator. The iron metal within agglutinates makes them magnetically susceptible, and thus this step concentrated agglutinates [e.g., 4,6]. However, past workers noted that 10–20% of the magnetic fraction is non-agglutinates, and <5 to >20% of the agglutinates remain in the nonmagnetic fraction [7], which we also found to be true. Thus, we then manually refined the magnetically sorted samples with a tweezers, removing any magnetic non-agglutinates

from the separate and also recovering nonmagnetic agglutinates from the low-agglutinate remnant.

Both separation methods were employed on separate splits of a single sample (62231) for comparison. Minor differences in reflectance and slope of the visible–near-infrared (VNIR) spectra were observed. Our assessment is that the magnetic-then-manual method resulted in a more representative agglutinate separate in comparison to the fully manual separate simply due to the difficulty in the manual separation process (inclusion of non-agglutinates) and possibly a bias toward the lowest reflectance agglutinates. The remaining samples were separated using the magnetic-then-manual method.

**Collection of Spectra:** We collected reflectance spectra at the Reflectance Experiment Laboratory (RELAB) at Brown University. A bidirectional spectrometer was used to gather spectra from 0.32–2.55  $\mu$ m and a Fourier-transform infrared spectrometer was used for 2–25  $\mu$ m. The measured samples consisted of agglutinate separates and unsorted soil from each of the samples (two separates from 62231), plus the low-agglutinate remnant from 62231. For 15041 and 62231, the agglutinate separates and unsorted soils were measured at eleven different geometries over the bidirectional spectrometer’s range, with a common incidence angle of 30° and an emission angle ranging from 45° to –75° (phase angles 5–105°). For all other samples the spectra were gathered at a single geometry, with an incidence angle of 30° and an emission angle of 0°. A calcite depolarizer was used to depolarize incoming light from the lamp, but was removed from the setup when measuring reflectance at wavelengths >1.8  $\mu$ m due to calcite absorption features. The spectra were calibrated using Spectralon, with a correction for spectral features that arise in Spectralon at wavelengths >2.15  $\mu$ m.

**Results:** VNIR reflectance spectra for unsorted regolith and agglutinate separates are shown in Fig. 1. For the Apollo 16 samples of varying maturity (Table 1), the submature sample 61141 is lower in reflectance with a steeper slope than the mature sample 62231, a result that was also found by Taylor et al. [8], but that does not fit the typical procession of space weathering (decreasing reflectance and increasing slope with increasing maturity). Despite differences in the spectra of the unsorted Apollo 16 soils, the submature and mature agglutinates share similar VNIR spectra. The agglutinates separated



**Fig. 1.** Left: Reflectance spectra of Apollo 16 samples (125–250  $\mu\text{m}$ ), which include unsorted samples and separated agglutinates (concentrated magnetically then manually refined). For mature sample 62231 the low-agglutinate remnant is also shown; spectra of the agglutinate separate from immature sample 67461 has not yet been collected. Right: Spectra of unsorted and agglutinate separates from mature Apollo 14, 15, and 17 samples.

from immature soil 67461 are moderately higher in reflectance with a stronger absorption band compared to their submature and mature counterparts. The agglutinate separates from samples 14259, 15041, and 79221 vary in reflectance in accordance with differences in the spectra of the corresponding unsorted regolith samples.

We find that all of the agglutinates separates have a substantially steeper (redder) continuum slope than unsorted soils, as seen in spectra that have been normalized at 700 nm (Fig. 2). The soil that remains after manually removing most agglutinates from sample 62231 (the low-agglutinate remnant) is notably shallower in slope than the unsorted sample – its slope is in fact comparable to the immature sample 67461 (Fig. 2).

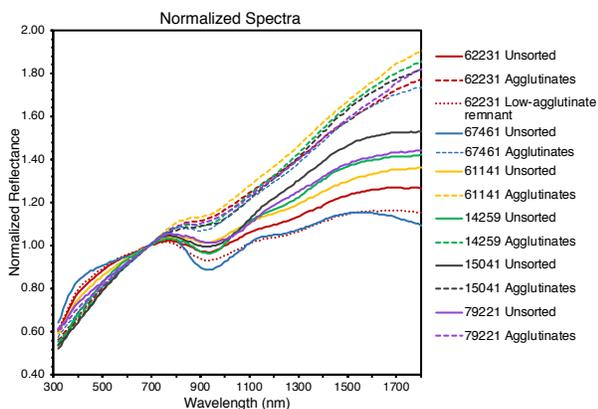
**Discussion:** The compositional analyses of these agglutinates [9] indicate that their glass fraction is typically  $\sim 35\%$  of their volume (the remaining fraction is mineral fragments), and is compositionally similar to the bulk soil. Thus the glass, with its broadened absorption bands, contributes only a limited amount to the

overall weakening of absorption bands within agglutinates (Fig. 2); it is the nanophase-iron (npFe) within agglutinates that dominates their spectra.

In comparison to the npFe-bearing silica gels of Noble et al. [10], the low-agglutinate remnant of sample 62231 most closely matches the 10–25 nm npFe at a concentration of 0.02 wt% Fe, unsorted 62231 best matches a npFe concentration of 0.06 wt% Fe, and the 62231 agglutinate separate best matches the same size range of npFe, but at a concentration of 0.13 wt% Fe. Thus the results here suggest that while agglutinates indeed contain larger particles of iron metal than those found in soil rims [e.g., 1–3, 11], the size range is broad such that the net effect of npFe in the agglutinates is to both redden and darken. At lower abundances, such as may be found within soil grain coatings, npFe contributes little to reddening [10]. The result that agglutinates are responsible for the majority of reddening in mature soils is in marked contrast to expectations based on previous work [e.g., 5, 12].

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**Fig. 2.** Reflectance spectra normalized at 700 nm for unsorted samples, agglutinate separates, and a low-agglutinate remnant.