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SPACE WEATHERING: LABORATORY ANALYSES AND IN-SITU INSTRUMENTATION.

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Introduction: Space weathering is now understood to be a key modifier of visible and near infrared reflectance spectra of airless bodies. Believed to be caused by vapour recondensation after either ion sputtering or impact vaporization, space weathering has been successfully simulated in the laboratory over the past few years [1]. The optical changes caused by space weathering have been attributed to the accumulation of sub-microscopic iron on regolith grain surfaces [2]. Such fine-grained metallic iron has distinctive magnetic properties that can be used to study it.

Extensive analysis of the magnetic properties of lunar regolith was performed in the years following the return of the Apollo samples [3]. However, this analysis has not been repeated on samples that can be matured under controlled conditions in the laboratory. Such a study would allow us to understand better the results of these earlier analyses as well as providing useful data about, for example, the amount and size of sub-microscopic iron grains produced, important parameters in space weathering.

The aim of this research was to begin this task by establishing a simulation facility in which powdered samples could be weathered in a controlled way, in particular at a range of temperatures. This was considered important to compare how the relatively well-understood lunar weathering process might differ on Mercury, the target of two upcoming spacecraft missions, MESSENGER and BepiColombo.

A suite of analyses was then applied to confirm the expected changes in the VIS-NIR reflectance spectra and study the corresponding magnetic properties of the samples. These analyses were designed to give information on the size distribution of any sub-microscopic iron produced, a parameter on which both the optical and magnetic properties of weathered planetary regoliths depends. First results are presented here.

Experimental procedure: Samples of San Carlos olivine (Fo_{90}) were crushed and dry sieved to < 63 µm and the resultant loose powder placed in an alumina crucible under a vacuum of better than 5×10^{-6} Torr. Samples were scanned with an IR (1064 nm) laser firing at 5 Hz with a pulse duration of 10 ns, a spot size of 1 mm and a pulse energy of 80 mJ. Samples could be baked out or irradiated at temperatures of up to 500°C if necessary. All samples were allowed to cool before air was admitted to the chamber.

Magnetic analyses: Sasaki *et al.* have shown that sub-microscopic iron can be identified by TEM and ESR in laser irradiated samples [1]. TEM is an extremely powerful technique and has been used to measure the size distribution of iron on lunar grain rims [4], but can necessarily only work on a microscopic scale. The techniques described here operate on bulk samples.

Magnetic susceptibility. Since olivine is a paramagnetic mineral, small quantities of a ferromagnetic phase, such as iron, should produce a noticeable increase in magnetic susceptibility. All samples were measured both before and after irradiation using a Bartington MS2-B instrument. This sensor works as an inductance bridge operating at a low frequency. All irradiated samples showed an increase in susceptibility with laser exposure. High frequency measurements were also attempted. Unaltered samples showed no frequency dependence, but irradiated (“weathered”) samples showed a decrease in magnetic susceptibility with frequency. This behaviour is typical of a superparamagnetic material; calculations show that for pure metallic iron, the superparamagnetic-single domain (SPM-SD) transition occurs at 9.9 nm for the high frequency and 11.2 nm for the low. Magnetic grains between these two sizes must therefore be created during irradiation.

Mössbauer spectroscopy. This is the most obvious tool to look for the reduction of Fe^{2+} to Fe^{0}. First results are shown in Figure 1. The spectrum does not show any obvious signature of metallic iron, but this is most probably just because the amount of metallic iron is so low relative to the Fe in the olivine itself.

Ferromagnetic resonance. Ferromagnetic resonance spectra were obtained with a Varian E109 ESR spectrometer. As expected, these show a strong resonance feature with g=2.1 and $\Delta H\sim65$ mT, similar to both the lunar regolith and previous weathering analogues.

Thermomagnetic analysis. Attempts were made to detect the unique Curie temperature of metallic iron at 1050 K, but these were unsuccessful due to oxidation of the (presumed) fine-grained iron, even with an argon purge. However, a trace ferromagnetic impurity was found in the olivine.

Vibrating sample magnetometry. Measuring the hysteresis curve should yield a variety of information about the amount of ferromagnetic and paramagnetic material. The previously mentioned ferromagnetic impurity prevented quantative analysis here, but this technique should be explored further.

Optical analyses: Bidirectional reflectance spectra were recorded to confirm the reddening and darkening associated with space weathering. These were indeed seen in all irradiated samples. A much more pronounced change was observed in those samples that had been baked out to 300ºC and allowed to cool before irradiation. Figure 2 shows one such spectrum; there is clear evidence of reddening and darkening.

Using Hapke's model for space weathering [2], it is possible to calculate the amount of sub-microscopic iron that is required to produce a given weathered spectrum. This process is also shown in Figure 2 where the iron has been assumed present only at the surface of grains that have no internal scatterers. The required amount of iron is very small, in agreement with the negative Mössbauer results and also with calculations of the amount of iron required to produce the observed increases in magnetic susceptibility.

***In situ* measurement of space weathering:** The magnetic susceptibility measurements made here proved to be a very sensitive indicator of the presence of superparamagnetic metallic iron. Such measurements lend themselves extremely well to inclusion on a planetary or asteroidal lander, being low power and low mass. Hence a multi-frequency susceptibility sensor, based on an inductance bridge, should be considered for future payload development.

Conclusions: Pulsed laser simulation of space weathering is a relatively new field and there is much scope for systematically studying space weathering and how it might occur on different bodies. In addition, magnetic laboratory techniques are extremely useful for determining the nature (amount, domain state) of the iron produced. One of these techniques, multi-frequency measurement of magnetic susceptibility, would be ideal for determining the presence and approximate size of iron grains *in situ* on a planetary or asteroid surface. Such a sensor would give local information about regolith maturity and the degree of weathering, allowing better removal of the spectral effects of space weathering from remotely sensed data.

References: [1] Sasaki S. et al. (2001) *Nature, 410,* 555–556. [2] Hapke B. (2001) JGR, *106,* 10,039-10,074. [3] Fuller M. (1974) *Rev. Geophys. Space Phys.*, 23–70. [4] James C. L. et al. (2003) *LPS XXXIII*, Abstract #1827.

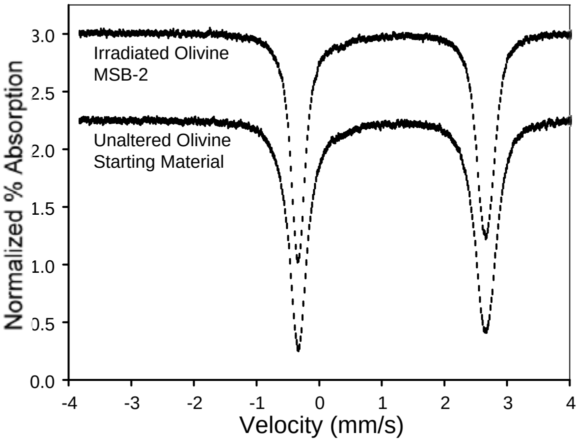

Figure 1. Mössbauer spectrum of unaltered and laser irradiated San Carlos olivine. Both spectra are identical, showing no signs of metallic iron.

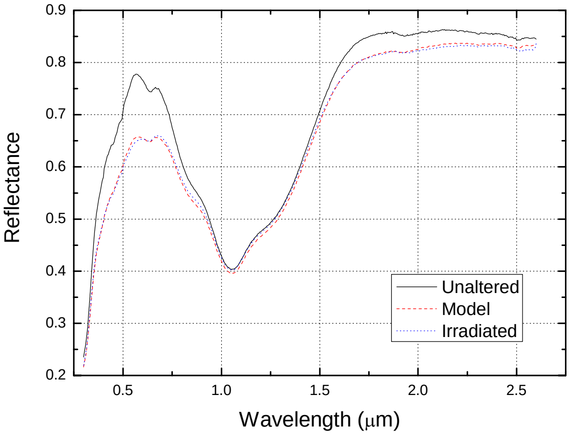

Figure 2. Bidirectional reflectance spectra of San Carlos olivine. The three spectra show the signatures of unaltered olivine, an irradiated sample and a numerically weathered (model) spectrum.

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