In situ measurement of space weathering in support of remote mineralogy

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1. What is space weathering?

The Moon is a unique body for which we have remotely sensed data, *in situ* measurements and returned samples for terrestrial analysis. When the first lunar samples were studied it was apparent that rock and regolith specimens with similar mineralogy had significantly different optical and magnetic properties.

An example of this is shown in *Figure 1* in which the VNIR reflectance spectra of rock and regolith samples are plotted. The regolith spectrum is considerably darker, exhibiting a reddened continuum and subdued absorption features. These changes confound attempts to perform quantitative mineralogy remotely.

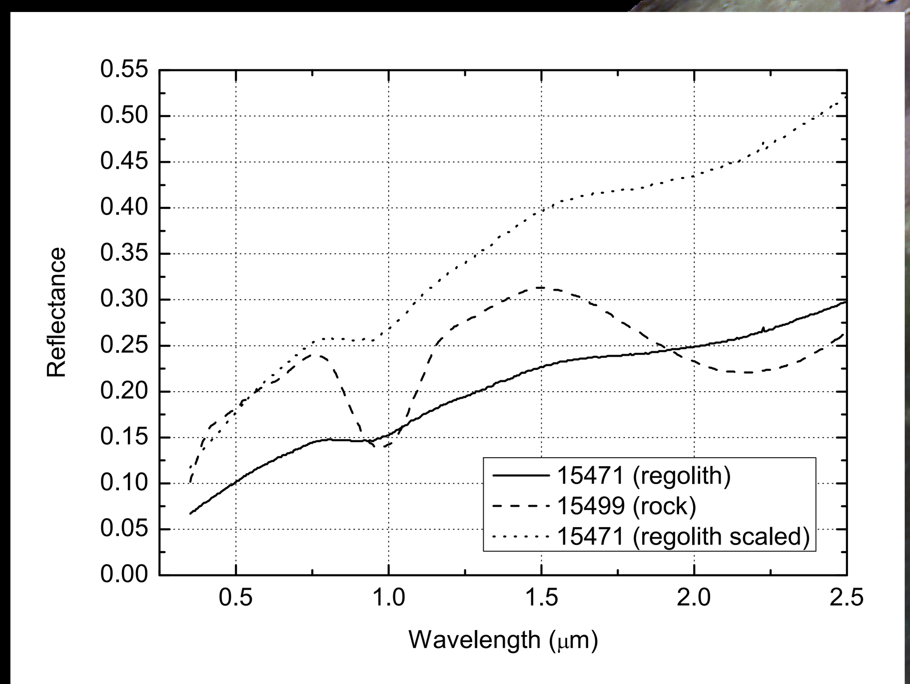

Figure 1

In recent years, research on space weathering has converged to show that these effects are caused by the reduction of ferrous iron to sub-microscopic metallic iron (SMFe). This process is driven by both micrometeorite impact and solar wind sputtering, resulting in ubiquitous deposits on almost all grains (*Figure 2*).

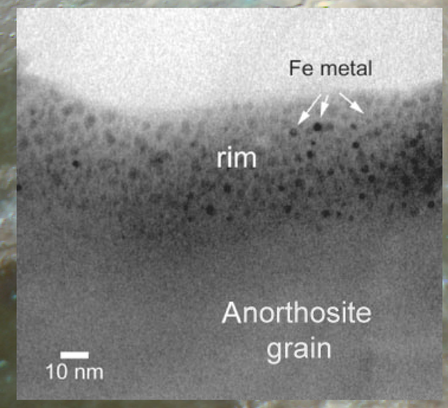

Figure 2

2. Optical effects of space weathering

Hapke (2001) has shown that reflectance spectra can be numerically "weathered" given the mass and size distribution of SMFe. In *Figure 3* the spectrum of a San Carlos olivine sample is plotted. This sample was then irradiated using a pulsed laser to simulate micrometeorite bombardment (Bentley, 2004). The effects of space weathering are apparent in the weathered spectrum. Hapke's technique was then used to weather the original spectrum until a best fit to the weathered spectrum was achieved at 0.00067 wt% Fe.

This technique can also be used in reverse to remove the effects of weathering if the amount of iron is known. *In situ* measurements of the SMFe content can therefore be used to remove weathering trends from the data.

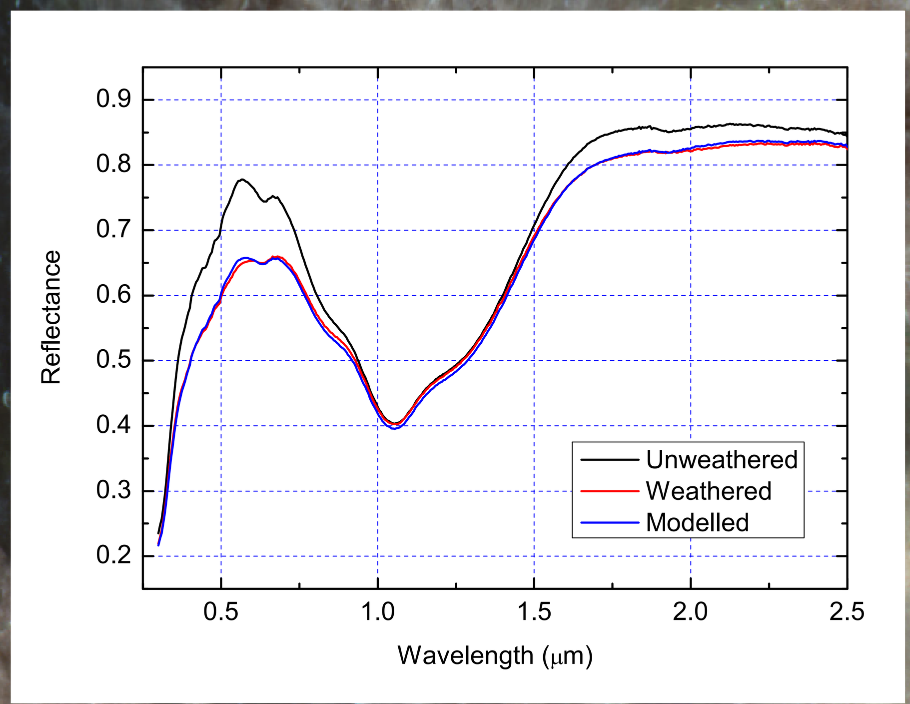

Figure 3

3. Magnetic effects of space weathering

Metallic iron is the dominant ferromagnetic phase in lunar mineralogy. Magnetic techniques are hence very sensitive to SMFe. Being fine-grained, SMFe is superparamagnetic (SPM), with a magnetic susceptibility (χ) orders of magnitude higher than single domain (SD) materials. Measuring χ at different temperatures and frequencies shifts this SD/SPM boundary and allows magnetic sizing, as shown in *Figure 4* (data taken from Stephenson (1971)).

Increasing the measurement frequency causes grains that were previously SPM to become SD, reducing the overall magnetic susceptibility of the sample. This frequency dependence is a very sensitive indicator of SPM material and hence SMFe in the lunar case.

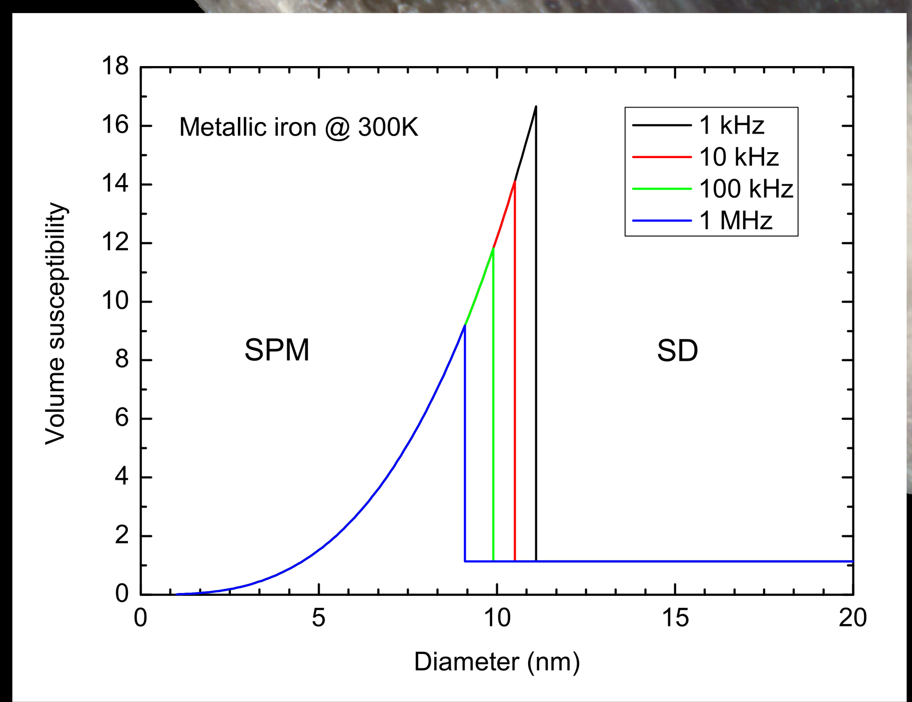

Figure 4

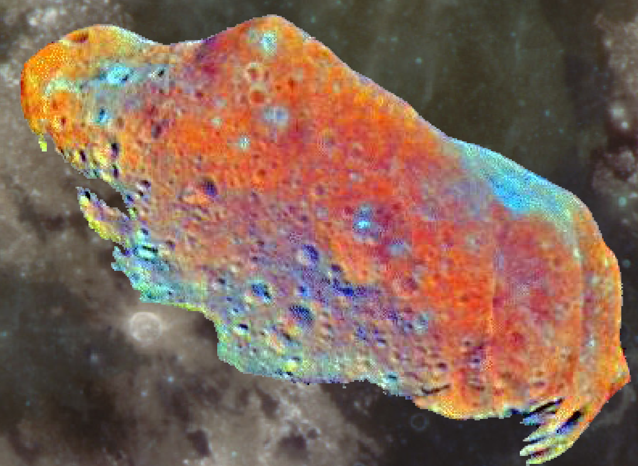
Figure 5

4. Space weathering in the solar system

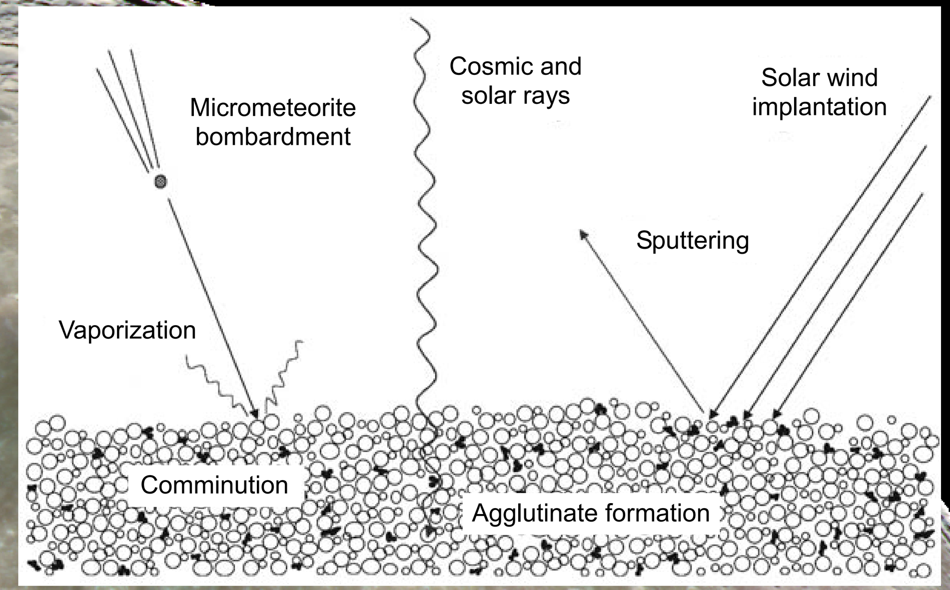

Figure 6

Our understanding of space weathering comes almost exclusively from th, but similar processes are expected on other airless bodies. Weathering has already been observed on asteroids, for example *Figure 5* shows a false colour image of Ida demonstrating the weathering trends.

Figure 6 summarises the key regolith maturation processes. The dominant weathering agents (micrometeorite impacts and ion sputtering) will have different strengths throughout the solar system, but with similar effects as on the Moon. Further modelling and laboratory studies are needed, particularly to prepare for the arrival of MESSENGER and BepiColombo at Mercury in the absence of any *in situ* measurements there.

5. Laboratory Measurements

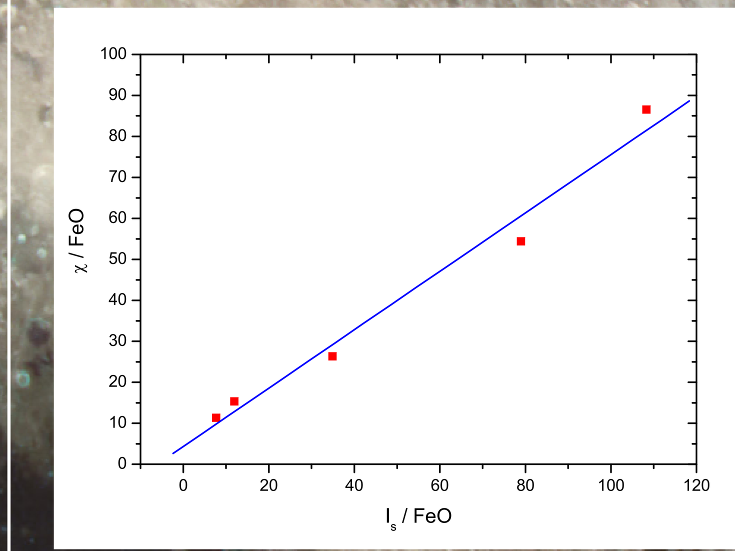

Figure 7

Electron spin resonance spectroscopy of lunar soils detects metallic iron spheres with diameters of between 4 and 33 nm. The intensity of this resonance, normalised to the wt% FeO provides the best maturity metric (Morris, 1976).

Magnetic susceptibility depends on the mineralogy of the sample, but is dominated by the amount and size of SMFe present. Plotting χ/FeO against I_s/FeO (*Figure 7)* shows a good correlation, hence this should also be a useful maturity and weathering index (Oder, 1992).

6. Instrument Proposal

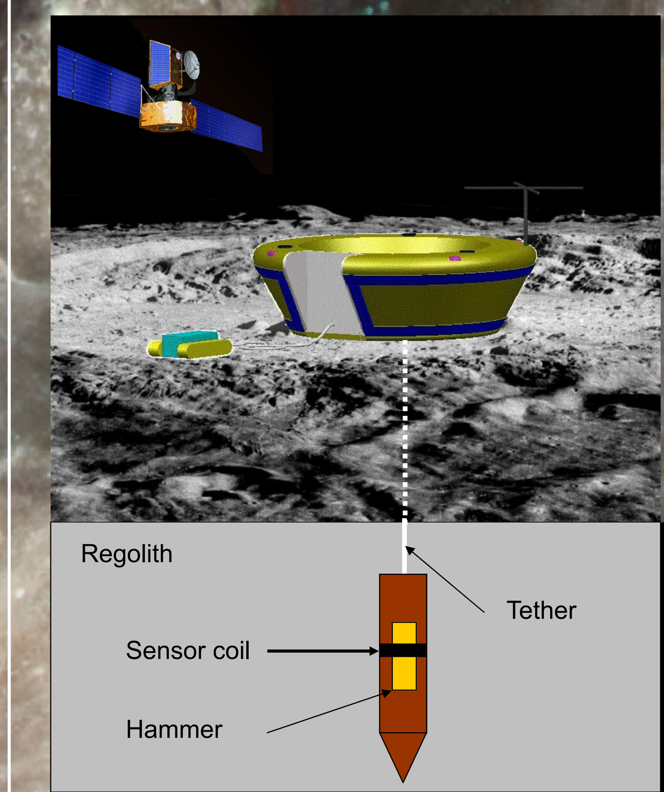

Figure 9

Magnetic susceptibility is well-suited to miniaturisation for spaceflight (*Figure 8* shows a commercial hand-held sensor). It has been shown to act as an index of maturity (weathering degree) and can be used to estimate the size distribution of SMFe, vital data for removing the effects of space weathering from remote reflectance spectra.

The basis of such a sensor is a coil, placed close to or in the regolith. The coil is energised with an alternating current to produce a low field (~0.1 mT). Its inductance then changes with the magnetic susceptibility of the regolith it couples to. Multi-coil techniques increase the depth of penetration; in this case one coil is energised and the others are receivers. This sensor can be deployed on a lander foot, rover, or mole, as shown in *Figure 9*, in which the coil is coaxial with the mole.

Figure 8

A development programme to produce a breadboard model of this instrument could be undertaken at modest cost. Amongst the key issues to be addressed are the thermal and mechanical stability of the coils, and how such a relative measurement would be calibrated. In the case of a mole careful choice of the hammering mechanism alloy could prove ideal.

7. Acknowledgements

Mark wishes to acknowledge PPARC for funding this research.
Figure 2 is taken from Pieters *et al* (2000).
The spectrum in Figure 1 was acquired by J.B. Adams and in Figure 3 by C.M. Pieters and T. Hiroi using the NASA RELAB facility at Brown University.
Figure 6 is courtesy of Sarah Noble.
Figure 8 is taken from http://www.zhinstruments.cz/sm-30.html
Figure 5 and the background image are © NASA

7. References

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