Sample Return from Permanently Shadowed Regions for Space Weathering Investigations

Among the important science objectives noted in key community documents including the Lunar Exploration Roadmap, the ASM-SAT report, and the National Academies reports is a better understanding of the role of space weathering and the solar wind specifically in the alteration of surfaces, regolith formation, and delivery and loss of volatiles. Crewed missions to the lunar polar regions provide the opportunity to obtain samples necessary to understand how space weathering occurs in cold and permanently shadowed regions and how polar space weathering influences the lunar volatile budget.

In situ measurements done on the lunar surface will provide a wealth of information about regolith in polar regions. However, laboratory analyses of returned samples would allow us to gain significant understanding of space weathering processes that would not be possible with in situ measurements alone. Specifically, transmission electron microscopy (TEM) has been instrumental in the study and understanding of space weathering. Samples from Apollo have been studied at the micro- to nanoscales to show the presence of nanophase metallic Fe in the top 100-200 nm of most soil grains, which through experiments and modeling have been shown to be the main cause of the darkening and reddening of the visible to near-infrared wavelength range that is characteristic of lunar space weathering [1-5]. More recent work on the Apollo samples, making use of new instrumentation, has further elucidated the effects of space weathering due to both ion irradiation and micrometeorite bombardment, including presence of oxidized material and helium trapped in vesicles [6-8]. There are a number of key science questions that can only be answered by having returned samples from the lunar poles, specifically permanently shadowed regions:

- How does the lack of direct solar wind irradiation in permanently shadowed regions change the types, amounts, or degrees of space weathering features present in the samples, such as rim thickness and degree of amorphization; presence, amount, and size of $npFe^0$; presence and density of vesicles?
    - For vesicles that are present, how do volatile contents compare to samples from other locations?
- Are volatiles stored primarily in vesicles, interstitially, or only on surfaces?
- Are we able to differentiate effects due to low temperature from effects due to decreased solar wind flux?
- Do soil grains known to have been in contact with water ice display different alteration features at the nanoscale?

By answering these questions about lunar soil samples, we can better understand how and where water is formed and retained on the lunar surface and how hydrogen and helium might best be accessed for ISRU, as well as how the environments on other airless bodies, including temperature and hydration, may influence how space weathering occurs there. The Moon has long been one of our primary “laboratories” for answering broader questions about the Solar System and return of new samples from the polar regions will allow it to continue to serve in this way.

While the science questions posed here cannot be answered in detail without samples returned to Earth, the ideal samples would be collected from locations where comprehensive *in situ* measurements have also been done. Specifically, it would be important to know the basic composition of the region and that the sample was or was not representative of the broader area, possibly through basic spectroscopic imaging. Likewise, we would need to know the ice content of the surface before it as disturbed. For samples taken as a core, this would mean taking a core from near a trench, where measurements of the layers would be done before the core is taken and possible migration of volatiles occurs as the temperature changes due to exposure and sampling. Additionally, temperature measurements at the surface and down to the final sampling depth would be important for understanding how and when volatiles are trapped or able to migrate and affect ongoing alteration. While attempting to maintain a temperature profile measured for a core is likely prohibitive, there could be significant value in keeping samples at very low temperature until or even throughout preparation and analysis. Capturing or containing the volatiles that might be released at increased temperature would be key to understanding the mobility of many species on the lunar surface, although some migration of molecules within an individual sample during transport from the Moon might be unavoidable.

Carefully chosen and collected samples will be necessary for answering the important science questions posed above, but the questions we are able to answer once samples are in the laboratory will not be limited to these or even to space weathering-related questions in general. As the Apollo samples demonstrated, we may not even know yet all the questions we should be asking. Ideally, samples being studied to determine how they were affected by space weathering processes would be studied not only by TEM but also NanoSIMS, FMR, SEM, XPS, and synchrotron techniques, to name a few, all of which have been used on Apollo samples to enhance our understanding of lunar processes [9-12]. SIMS has also been used to help untangle indigenous and exogenous water sources [13,14]. More recently developed or adapted techniques, such as atom probe tomography [15] and nano-IR [16] would also be available once samples are returned to help address these questions and others. Many of these techniques require only small amounts of material each, making small amounts of well-characterized returned sample that remains in relative context more important for answering these questions than a large volume of spatially mixed material.

The key questions surrounding space weathering at the lunar poles and in permanently shadowed regions show that having carefully collected samples appropriate for TEM and complementary measurements in the laboratory would advance our understanding of these processes on the Moon and elsewhere in the Solar System.

References

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