CONSTRAINING THE RELATIVE ROLES OF THE SPACE WEATHERING PROCESSES THAT CREATE SUBMICROSCOPIC IRON ON THE MOON. A. P. Jordan[1,2], M. L. Shusterman[3], C. J. Tai Udovicic[4], [1]EOS Space Science Center, University of New Hampshire, Durham, NH, USA (first author email address: a.p.jordan@unh.edu), [2]Solar System Exploration Research Virtual Institute, NASA Ames Research Center, Moffett Field, CA, USA, [3]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, [4]Northern Arizona University, Flagstaff, AZ, USA.

Introduction: The Moon is exposed to a variety of processes that change the optical properties of the regolith, in part by creating submicroscopic iron ($smFe^0$) inclusions in the space weathered rims that form on soil grains. There are three possible sources of $smFe^0$: the solar wind, micrometeoroid impacts, and dielectric breakdown.

The solar wind creates inclusion-poor, amorphous rims on soil grains [1-2]. Solar wind simulations in the laboratory suggest that it may be a significant source of $smFe^0$, whether directly or via sputter deposition [e.g., 3-4], but evidence is emerging that the high particle fluxes in experiments cause changes that do not occur in the solar wind [2, 5]. Micrometeoroid impacts create inclusion-rich, vapor-deposited rims and agglutinates [1, 6] and are thus known to be a significant source of $smFe^0$. Finally, recent work has predicted that large solar energetic particle (SEP) events may cause extreme charging and breakdown in cold lunar regolith on much of the nightside and in permanently shadowed regions [7-8]. Dielectric breakdown has been predicted to melt and vaporize the regolith at rates slightly less than that of impacts, making it a potentially important source of $smFe^0$ [8-9].

A critical question, then, is the relative role of these weathering processes. To help answer this question, we develop a simple model for the formation of $smFe^0$. This model, when combined with orbital analyses of $smFe^0$, constrains the depths and timescales of the processes that create optically active $smFe^0$.

A model for submicroscopic iron: The majority of optically active $smFe^0$ is found in the space weathered rims on soil grains [10-11]. Because these rims are thin with respect to the host grains' diameters, the abundance of $smFe^0$ should scale linearly with the thicknesses of the rims. We develop a model for the growth of $smFe^0$ based on the analysis of [2], who measured the thickness of grain rims as a function of exposure time to the solar wind:

$$s(t) = s_{max}\left(1-\exp\left[\frac{-t_{SpWe}(t)}{\tau_{SpWe}}\right]\right) \quad (1)$$

where s is the abundance of $smFe^0$ (wt%), t is age of the surface (in units of Myr—see below), s_{max} is the maximum abundance of $smFe^0$ that can occur in the soil (grain rims have a maximum thickness of ~200 nm [2]), t_{SpWe} is the time the soil has been exposed to a given space weathering process, and τ_{SpWe} is the characteristic timescale of that process.

This model requires knowing how long the grains have been exposed to the process(es) forming the rims. The exposure time, in turn, is limited by impacts mixing the soil, creating a region of constant maturity [12]. We incorporate the measurements of [12] into the model of [13] to estimate how long (t_{SpWe}) impact gardened soil has been exposed to space weathering processes that penetrate a given depth z_{SpWe} into the soil:

$$t_{SpWe}(t) = \frac{z_{SpWe}}{2.2} t^{0.55} \quad (2)$$

where z_{SpWe} is in units of cm and t is in units of Myr (see [12]).

Equations (1) and (2) combine to describe how the abundance of $smFe^0$ grows and then reaches a steady-state for $t_{SpWe} > \tau_{SpWe}$. To test this model, we compare it to the results of [14], who calculated the abundance of nanophase (<33 nm) iron ($npFe^0$) in craters' ejecta blankets in the highlands (between ±60°latitude) as a function of the craters' ages (data points in Fig. 1). If the space weathering timescale $\tau_{SpWe} \approx$ 1-10 Myr [e.g., 2], then the model fits the data for $z_{SpWe} \approx$ 0.1-1 cm (solid curve in Fig. 1).

Discussion: Our simple model combines trends from studies of Apollo cores and measurements of individual grain rims, yet it accurately fits orbital observations of space weathering. This deep correlative consistency gives us confidence that our model correctly describes how space weathering produces optically active $smFe^0$ on the Moon. It thus has an important implication for the processes that create $smFe^0$.

The depth down to which the processes likely work is ~0.1-1 cm. This is much deeper than the penetration depth of the solar wind. Consequently, it does not seem that the solar wind plays an important *direct* role in the creation of $npFe^0$. It may play a role in creating the reducing environment conducive for the formation of $npFe^0$ [15], although there are difficulties with this model [3, 16].

Micrometeoroid impacts, on the other hand, can explain this characteristic depth, because they can penetrate ~0.1-1 cm into the soil. This is consistent with the fact that most $npFe^0$ is found in vapor-deposited rims [1].

As mentioned above, another possible source of $smFe^0$ is dielectric breakdown. It has been predicted to work at rates similar to impacts, and it operates to depths of ~0.1 cm [7-8, 17]. Consequently, breakdown could also contribute to the creation of $npFe^0$, consistent with the results of [9].

In addition, we find that the abundances of $npFe^0$ and >33 nm microphase iron ($mpFe^0$) is well-correlated throughout the highlands (Fig. 2). This linear correlation means that the two size ranges form on similar timescales (with respect to the age of the surface *t*). Thus, the two appear to be produced by the same set of processes, rather than the solar wind dominating the production of smaller $smFe^0$ and micrometeoroids the production of larger $smFe^0$, as some have argued [e.g., 18]. As a result, we conclude that micrometeoroid impacts, and possibly dielectric breakdown, dominate the formation of $smFe^0$ in the lunar highlands. The solar wind, if it plays a role, only helps impacts and breakdown form $smFe^0$, by creating a reducing environment.

Conclusion: We create a simple model that synthesizes analyses of Apollo soils and orbital data. With it, we find that the production of $smFe^0$ is likely dominated by micrometeoroid impacts, with a possible contribution from dielectric breakdown.

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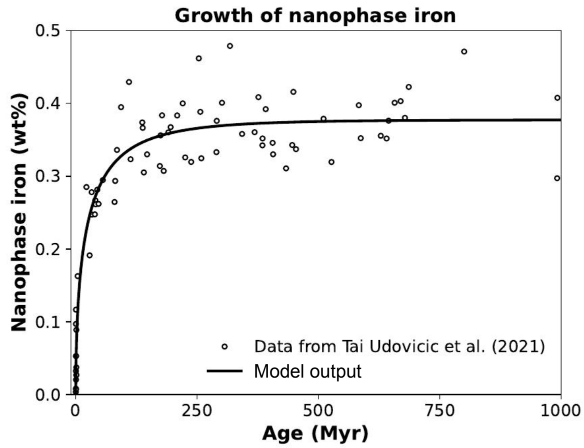

Fig. 1. How the abundance of $npFe^0$ in the lunar highlands depends on the age of the soil. The data points are from the study of [14], and the model output (solid line) is from the combination of equations (1) and (2). The good fit constrains the process(es) that create $npFe^0$.

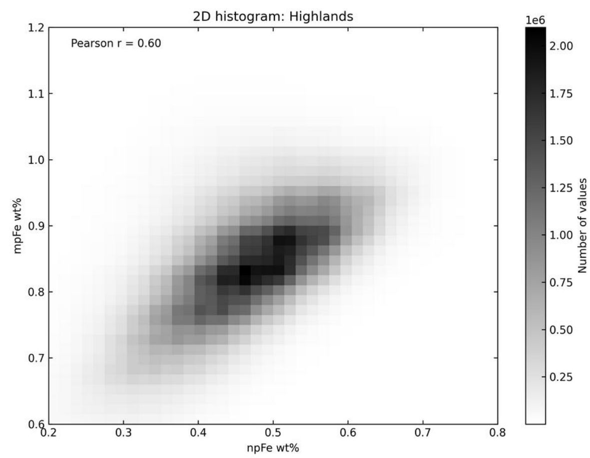

Fig. 2. The abundances of $mpFe^0$ (>33 nm) and $npFe^0$ (<33 nm) are well-correlated (data from [19]). For this to be the case, they must form on similar timescales. Thus, instead of, e.g., $npFe^0$ being created mainly by the solar wind and $mpFe^0$ being dominated by micrometeoroid impacts, both size fractions are likely created by the same set of processes.