THE ROLE OF SOLAR WIND ION PROCESSING IN SPACE WEATHERING OF OLIVINE: UNRAVELING THE PARADOX OF LABORATORY IRRADIATION RESULTS COMPARED TO OBSERVATIONS OF NATURAL SAMPLES.

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Introduction: Ion irradiation by the solar wind plays a major role in space weathering [1]. Among its multiple effects are ion damage and implantation processes that alter the crystal structure as well as chemical composition of the outer few 100 nanometers of space exposed regolith grains [1]. This forms a portion of the space weathered rims on lunar and asteroidal regolith grains that is uniquely ion-processed [1]. One aspect of these *ion-processed grain rims* is the possible link between their widths, and degree of ion damage, and the length of exposure of their host grain on the topmost surface of lunar and asteroidal regoliths [2]. Ultimately, quantifying this link relies on laboratory ion irradiation experiments to calibrate the ion fluence or dose at which different degrees and depths of ion damage occur. Here we discuss evidence, specifically from the mineral olivine, suggesting there may be limitations in extrapolating the results of laboratory ion irradiation experiments to natural ion irradiation by the solar wind.

The Paradox of Solar Wind Ion Damage in Olivine. The first TEM studies of lunar ion-processed grain rims, mostly in plagioclase, described their structure as amorphous [3]. Amorphization has since not been found to occur in rims on all minerals, however [2,4]. For olivine in particular, transmission electron microscope (TEM) studies of olivine grains in mature lunar soils [2], from the surface of asteroid Itokawa [4], and on the solar wind-exposed surfaces of lunar rocks [2], have found their ion-processed rims have high defect densities, but lack complete amorphization of any part of the rims.

The case of olivine on the space-exposed surface of lunar rock 64455, which we have previously described [2], is particularly enigmatic relative to experimental results. The surface exposure age of the host rock is independently well-constrained from isotopic measurements to be 2 My [5]. This exposure age converts to solar wind exposure fluences for the rock's surface of 10^{21} to 10^{22} ions cm^{-2} for solar wind H^{+} and 10^{19} to 10^{20} ion cm^{-2} for He^{+}. In laboratory ion irradiation experiments using He^{+} at solar wind energies, olivine has been found to undergo complete amorphization at fluences in the 10^{16} ions cm^{-2} range [6]. Paradoxically, however, olivine grains directly exposed to the solar wind on the surface of 64455 *show no amorphization in TEM observations*, only a high-defect density microstructure [2] Yet there is every indication that, from solar wind He^{+} ions alone, they have received fluences 5-6 orders of magnitude higher than those which amorphize olivine under relevant solar wind conditions in the laboratory [6].

Possible explanations for the paradox of olivine on lunar rock 64455 include: 1) errors in previous laboratory amorphization fluence calibrations [6], 2) deviations in the nominal exposure age of the 64455 olivine grains studied by [2] relative to the bulk host rock because of changes in the rock orientation, erosion of its surface by sputtering or micrometeorite impact, or temporary burial, 3) an effect of the 5-6 orders of magnitude difference in ion flux between the laboratory experiments and the solar wind [2].

With regard to errors in the laboratory amorphization fluence measurements, we performed a re-check of the original laboratory measurements performed using San Carlos olivine by [6]. Our irradiations were performed in a PHI-560 XPS instrument at UVa using the same 4 keV He ion energy as [6], and an ion flux/dose rate of 1 x 10^{13} ions cm^{-2} s^{-1}. Flat-polished bulk San Carlos single crystals were used in place of the pre-ion milled samples used by [6]. FIB sections preserving the irradiated top surface of the sample were prepared to minimize side wall milling/damage effects from the Ga^{+} beam. Characterization using the JEOL 2500 field-emission scanning transmission electron microscope (FE-STEM) at NASA JSC showed the initiation of complete amorphization of the top 10-20 nm of the sample at 2.1 x 10^{16} He^{+} ions cm^{-2}, with an underlying partially damaged/defective layer of equal thickness. At higher fluences of 5.1 x 10^{16} to 1 x 10^{17} ions cm^{-2} He implantation bubbles develop similar to those reported by [6] at similar fluences. The results are well within an order of magnitude of confirmatory agreement with the amorphization fluence of 5 x 10^{16} He^{+} ions cm^{-2} measured by [6].

For 64455 an effect from rock burial has previously been discounted because the isotopic exposure age clocks shut-off during burial [2,5]. 64455 is also unlike other rock fragments on the lunar surface in that it was completely coated by a large splash of impact glass when it formed, and the surface olivine is a devitrification product in that glass [2]. “Zap pit” micrometeorite craters on the glassy surface clearly show where impacts eroded the surface and where they did not, indicating the rock has not turned over since being exposed on the regolith surface [2,5].

Unraveling the Paradox: A Role for Damage-Rate and Dynamic Recovery Effects. In light of the previous considerations, we are examining the alternative possibility that the 5-6 orders of magnitude lower flux of the solar wind compared to laboratory experiments may place the natural samples into a regime where the damage rate is low enough to be compensated by dynamic recovery processes. The implication is that a dose rate (or alternatively damage rate) effect exists in olivine radiation-induced amorphization which may or may not be accessible in the experimental dose rate/ion flux regime, but may come into play at the extremely low dose rate/damage rate of natural samples.

Dose rate effects have been noted in radiation-induced amorphization of various materials [7,8]. In semiconductors the direction of the effect matches what may be occurring for olivine: higher dose rates (higher ion flux) promote amorphization, specifically lowering the critical fluence (dose) required for solid state amorphization to occur [7]. But the effect is not seen in all materials, and evidence for an opposite effect has also been noted [8]. Some initial experimental evidence for a dose rate effect in olivine has been reported by [9], but additional critical experiments are needed.

Current models for radiation-induced amorphization of ionic crystalline solids by low energy, low mass ions are mostly based on the balance between collisional point defect accumulation, with promotes amorphization [10], and recovery by re-arrangement of point defects into lower-energy extended defects by diffusion [8,10]. Amorphization resistance occurs in those structures where the simplicity of the crystal structure contributes both to rapid diffusion and extended defect creation [10]. We have previously reported such behavior in sulfides [11].

Conventional and high-resolution TEM images suggest that extended defect formation, in the form of isolated dislocations, dislocation arrays and sub-grains, is characteristic of the partially ion damaged grain rims in natural olivine [2,4]. The same microstructure appears in the un-amorphized portions of the ion-damaged regions produced in our current experiments. As illustrated in Fig. 1, the sub-grains are characteristically on the order of 5-10 nm in size. To the extent that the sub-grain walls act as sinks for collisionally-generated point defects, the short diffusion-length scale for removing these defects may promote point defect removal fast enough to compensate for the buildup of anti-site and other point defects inside the domains. (It is the increase in lattice energy generated by this build up that has been shown to trigger amorphization in olivine [10].) The sub-grain domains therefore remain stable against amorphization irrespective of the accumulated fluence, keeping the structure nanocrystalline, but not fully amorphous.

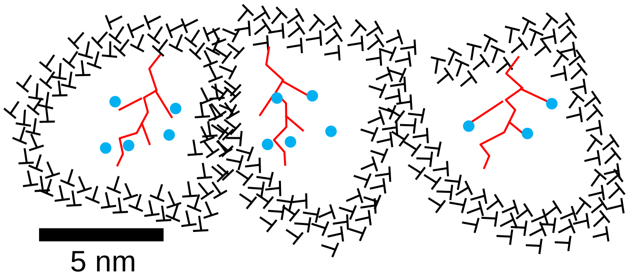

Fig. 1. Illustration of nanoscale sub-grain development at an intermediate stage of solar wind ion damage in olivine, with generation of point defects (blue) by ion collision cascades (red).

Conclusions and Implications. Our suggested model hinges on the 5-6 orders of magnitude slower rate for point defect generation inside the sub-grains in natural samples compared to experimental irradiations. It assumes that volume diffusion inside the domains is fast enough to allow the shorter diffusion length scale to promote defect removal faster than ion collisions create defects. We are in the process of testing this assumption using TRIM calculations to model point defect generation rates at solar wind fluxes, combined with diffusion models as well as additional lower ion flux irradiation experiments. Supporting evidence from this work would have significant implications for the extrapolation of laboratory ion irradiations experiments to solar wind space weathering effects in olivine, as well as other minerals.

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