SPACE WEATHERING OF FE-POOR SILICATE REGOLITHS: EXPERIMENTAL AND THEORETICAL SIMULATIONS.

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Introduction: Surfaces of airless solar system bodies are optically modified by space weathering processes. Fe-bearing silicates darken and redden due to reduction of Fe^{2+} and/or Fe^{3+} to Fe^{0}. Some regoliths, e.g., on Mercury and some asteroids, may be poor in FeO and it is important to assess how their albedos and optical spectra may be modified by space weathering. We performed spectral reflectance and SEM/TEM studies of a natural plagioclase (andesine-labradorite) irradiated with a nanosecond pulsed laser. We also employed theoretical modeling to characterize optical modification of Fe^{2+}-poor regolith due to formation of nanophase Fe^{0} (npFe^{0}) inclusions.

Samples and Experimental Procedures: A natural andesine-labradorite (An$_{47-52}$) [1] was magnetically separated and hand-picked to remove accessories such as biotite and ilmenite. After these procedures, bulk chemistry of the sample shows 0.77 wt.% FeO, while pure plagioclase grains contain <0.08 wt.% FeO [1]. The major sources of FeO in the sample are traces of mica, ilmenite, and low-Ca pyroxene (En$_{71-74}$).

To simulate micrometeorite bombardment of an FeO-poor target comparable to the hermean regolith and other FeO-poor silicate targets, two pressed pellets of the powdered (<75 µm) plagioclase were irradiated with 20 mJ nanosecond (6-8 ns) laser pulses (NdYAG laser; λ=1064 nm; pulse frequency 20 Hz [2]). One pellet was exposed to a single scanning irradiation, while the 2nd one was scanned twice. Energy density was 160 mJ$*$mm^{-2} for a single scanning experiment and 320 mJ$*$mm^{-2} for the pellet scanned twice.

Biconical reflectance spectra (0.45-18 µm) were acquired at i=e=20° using a Bruker IFS88 FTIR-spectrometer with a variable angle "Seagull$^{\text{TM}}$" reflectance accessory.

A Zeiss 1540 XB FIB-SEM was used to extract thin lamellae perpendicular the surface of a plagioclase grain. TEM was carried out using a Zeiss Libra 200FE TEM operating at 200 kV. EDX analyses were performed using a Technai TEM (LaB$_6$) operated at 200 kV and equipped with an EDAX EDS detector.

FIB/SEM/TEM Results: The irradiated surface areas/grains show evidence for significant melting. Not all plagioclase grains within the irradiated area were molten, rather some regions show more extensive melting compared to other areas (Fig. 1). Large (>10 µm) grains suffered less melting than the smaller (<5 µm) ones, the latter being often completely fused. The glass layer of non-uniform thickness (up to first microns) is sometimes vesicular. We found no npFe^{0}-inclusions within the glass layer during TEM studies. Glass droplets (10-15 µm in diameter) and many small (~1 µm) melt spherules of ilmenite composition were found between and over plagioclase grains in the irradiated region of the pellet. These findings are similar to the recently reported TEM study of laser-irradiated meteorites [3] but the lack of abundant npFe^{0} prevented us from the detection of a thin (~20 nm-thick [3]) vapor deposit layer, if present.

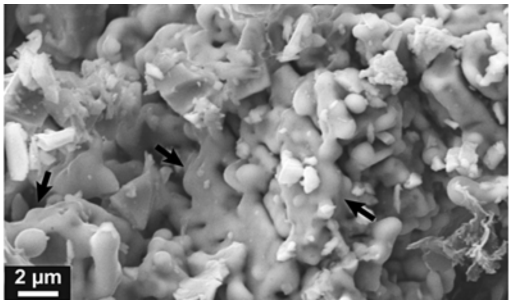

Figure 1. Secondary electron (SE) image of an irradiated (20 mJ$*$2) plagioclase pellet. Glass is indicated with arrows.

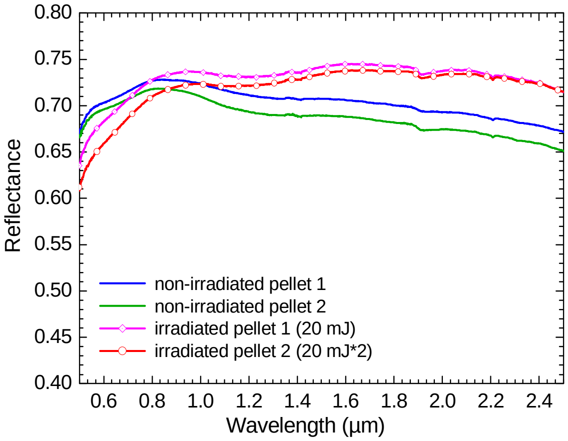

Figure 2. VNIR reflectance spectra of non-irradiated and irradiated areas of andesine-labradorite pellets.

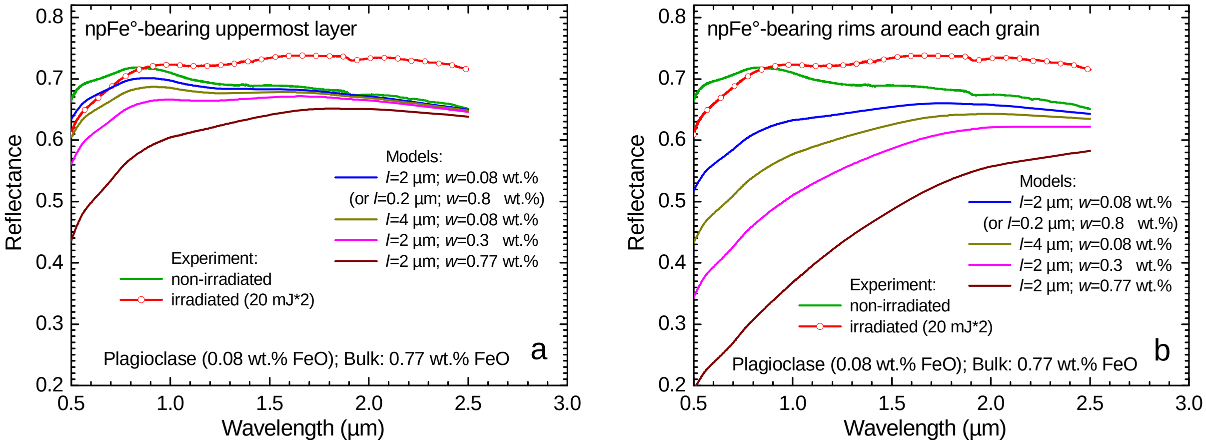

Figure 3. Calculated spectra of andesine-labradorite pellets, where the uppermost layer (a) or rims around all particles (b) contain npFe^0-spherules of <30 nm in diameter. *w* is weight percentage of FeO reduced and aggregated to npFe^0.

Reflectance Spectra of Plagioclase Pellets before and after Irradiation: Moderate reddening in the NIR (Fig. 2) and spectral changes in the mid-IR are likely to be textural effects induced by the laser-induced "gardening". Theoretical models suggest that the slight darkening in the visible, the shift of a local reflectance peak at ~0.8 µm to longer wavelength, and the absence of a weak broad charge-transfer absorption (0.6-0.8 µm) after irradiation are likely to be associated with reduction of Fe^{2+} and Fe^{3+} to Fe^0 within a quickly quenched glass layer on the irradiated surfaces.

Theoretical Modeling Results: Spectral alteration of regolith particles and pressed pellets by the presence of different volume concentrations ***c*** of npFe^0 (size <30 nm) inclusions embedded into surface layers of thickness ***l***, was theoretically simulated using the approach described in [4, 5]. Contribution of npFe^0 to optical density of the regolith particles strongly depends on ***l∗c*** (µm∗vol.% npFe^0). Fig. 3a simulates the situation observed after a laser-irradiation experiment, while Fig. 3b represents a case of a more mature regolith where all regolith grains are mantled with npFe^0-bearing rims of the same thickness ***l***. Optical alteration is much more effective in the latter case compared to the laser-irradiation experiment. Reduction of 0.77 wt.% FeO in micron(s)-thick rims can significantly darken and redden the regolith (Fig 3b). Comparison of calculated and measured spectra suggests that a fraction of bulk FeO could be reduced to npFe^0 in the top layer of the laser irradiated pellets. Due to large uncertainty in ***l*** this fraction is hard to constrain but the modeling suggests that: (1) Fe^{2+} and Fe^{3+} from impurities was likely involved in the process of iron reduction; (2) average ***l*** is probably >0.4 µm; (3) ***l∗c*** value (in µm∗vol.% npFe^0) could be on the order of 0.15 but likely to be <0.4.

Conclusions: Laser irradiation of a silicate target with low FeO content produced only mild optical effects. Optical alteration is mostly due to textural effects but some optical changes at wavelengths <1 µm are consistent with formation of npFe^0 in the uppermost surface layer. Calculations show this should occur in a micron(s)-thick quenched melt layer, rather than in a vapor deposit. According to our calculations, the latter one should contain at least 5-7 vol.% npFe^0 to produce even the mild optical effect observed in our experiment. The models also show that the effects strongly depend on the way how an npFe^0-bearing layer covers regolith particles. Optical maturation would be much more effective if regolith particles are mantled with npFe^0-bearing rims due to impact-induced turnover and repeated exposure to micrometeorite or solar wind flux. This and similar [e.g., 2] experiments, however, simulate effects of dust impacts into very immature regoliths (only the uppermost surface layer contains npFe^0). The fact that spectra of many asteroids are well reproduced by results of such experiments suggests that many asteroid regoliths are likely to be immature, while even low FeO contents can significantly affect albedos and spectral slopes of mature regoliths.

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