FEMTOSECOND LASER IRRADIATION OF OLIVINE SINGLE CRYSTALS: EXPERIMENTAL SIMULATION OF SPACE WEATHERING

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Introduction: The space weathering (SW) is one of the most common surface process occurring on atmosphere-free asteroids and on the Moon. It is mainly caused by the solar wind irradiation and the impact of micrometeoroids. At the micro- and nanometer scales, SW produces irreversible modifications, i.e., the formation of iron nanoparticles ($npFe^0s$), melting, recrystallization, fracturing, and development of dislocations. These damages concern the reflectance spectra of such bodies, impeding the correct interpretation of their surface mineralogy (e.g., [1], [2]).

Ion irradiation and laser experiments have been employed to simulate the effects of SW induced by the solar wind and micrometeoroid impacts, respectively (e.g., [3]). In order to constrain the mineralogical modifications of the SW and understand the mechanisms of mineral damages, we carried out new laser experiments using a femtosecond radiation on single olivine crystals.

Samples and Methods: Crystallographically oriented slices (thickness 300-500µm) of forsterite-rich ($Fo_{94.7}$) olivine were irradiated under vacuum (10^{-3} mbar) with a Ti:sapphire laser. The maximum applied laser pulse energy was 2.3 mJ at 100 fs pulse duration, offering a peak optical power of $2.3x10^9$ W. The laser spot was ~40 µm. These parameters correspond to a peak irradiance of ~10^{15} W cm^{-2}.

In order to acquire reflectance spectra in NUV-vis-NIR range grids (2.5 mm x 2.5 mm) of single pulse shots were produced on each sample. The morphology of the microcraters was characterized by white light interferometry and SEM. Then, cross-sections from the ablation pits and the crater rims were prepared by FIB-SEM and studied by TEM. Different orientations were investigated to prove if there is an orientation-dependence of shock effects.

Results and Discussion: The main advantage of our experimental approach compared to the previous nanosecond laser experiments is the high peak irradiance of the laser (10^{15} W cm^{-2} vs. 10^{10} W cm^{-2}). It is well above the physical limit of 10^9 W cm^{-2} able to generate a shock wave with a maximum initial pressure of few GPa [4]. According to the laser theory [5], the femtosecond radiation generates the propagation of the shock wave at the nanosecond timescale (i.e., timescale of the hypervelocity micrometeoroid impacts). The application of ultra-short laser pulses has two other advantages: the reduction of the heating induced by the interaction of laser light with the developing vapor plume and the possibility to focus the laser beam to simulate the effects of a single impact.

The combination of these factors results in the formation of microcraters (diameter ~80 µm and depth of ~3 µm), whose cross-sections show a layered structure compatible with the attenuation of the shock wave. Similar structures were found in microcraters of the regolith samples of the Moon [6] or the Itokawa asteroid [7]. Combining the TEM-EDX data and the textural features of the different layers, the passage of the shock wave induces melting (up to 0.8 µm), solid-state recrystallization and mosaicism (up to 1.8 µm), and fracturing and propagation of c-dislocations (up to 20 µm). During the melting of the topmost portion of the olivine, lighter elements (mostly O and Mg) are lost due to kinetic fractionation from the gas of the short-lived plume, meanwhile, siderophile elements (Fe and Ni) are reduced due to the high temperature, resulting in the formation of $npFe^0$. During the cooling, the melt layer partially crystallizes in its lower portion, forming a layer of olivine crystals with a palisade-like texture. Depending on the orientation of the samples, the thickness of the different layers can vary and fractures and dislocations can have different abundances. Towards the rims, the layers become thinner up to disappear.

The reflectance spectra of irradiated samples show the typical SW modifications, namely, darkening (overall reduction in spectral intensity) and reddening (relative spectral intensity increasing at higher wavelength).

Conclusions: The continuous development of laser facilities is of great interest for the planetary sciences. Through femtosecond laser irradiation, we successful reproduced both the spectral and microstructural modifications caused by the SW in olivine. Next steps include experiments in other minerals of planetological relevance.

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