SPECTRAL AND MICROSTRUCTURAL MODIFICATIONS OF OLIVINE UNDER ION IRRADIATION.

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Introduction: Atmosphere-less bodies of the Solar System are submitted to surface alteration processes (solar wind irradiation and micrometeorites impacts) collectively known as space weathering. Space weathering strongly modifies the spectral properties of their surfaces, usually darkening and reddening the VIS-NIR region of the spectrum and attenuating their characteristic absorption bands [e.g., 1-3]. The study of lunar and Itokawa samples by transmission electron microscopy (TEM) revealed that those changes are due to chemical and structural changes of the surface materials at the nanoscale, such as the formation of an amorphous rim typically 50-100 nm thick [e.g., 4-5]. Here we report on the spectral properties in the VIS-NIR and in the MIR and nanostructure studied by TEM of experimentally weathered Fe-rich olivine ($\approx Fa_{30}$) by ion irradiation.

Methods: Olivine samples were irradiated with 20-40 keV He and Ar ions with fluences ranging from 1 to $6x10^{16}$ ions/cm^2. The irradiated samples were studied spectroscopically in the VIS-NIR and in the MIR (part of the spectral properties are published in [6]). The microstructural characteristics of the modified surfaces were studied by transmission electron microscopy after FIB extraction, using conventional bright field imaging, HAADF imaging, EDXS and EELS spectroscopies.

Results: In the MIR range, we observed a shift of the silicate bands toward longer wavelengths that increases with ion fluence. In the visible-NIR range, the irradiated olivines show darkening and reddening. At the TEM scale, the sample irradiated with He at low fluence (10^{16} ions/cm^2) shows localized and partial amorphization at the predicted maximum implantation depth. In this area, the olivine lattice displays evidence of strong elastic deformation, as revealed by Bragg contrast perturbation on bright field images. At high fluences ($6x10^{16}$ ions/cm^2) the samples are almost fully amorphized and contain nanometer-sized vesicles due to the implantation and precipitation of He or Ar. The amorphous layers do not contain any Fe nanoparticules (npFe). Slight chemical evolution occurred with a preferential loss of Mg and O close to the surface. With a combined set of data obtained with HAADF imaging and EELS and EDS spectroscopies, we show that the density of the material strongly decreases. This is caused by a double contribution, on the one hand by the phase transformation (crystalline state to the amorphous state) and on the other hand by the implantation of incident ions and the formation of small vesicles.

Discussion: The absence of npFe in the irradiated layer suggests that they do not form by irradiation only. NpFe have frequently been observed in both lunar and Itokawa samples [e.g., 4-5]. However, they could be formed by a secondary process such as a precipitation induced by a thermally activated process. Experimental studies have shown, for instance, that nanoparticles can form by a vapor deposition process simulating micrometeorite impacts [e.g., 7]. Despite the absence of npFe, the spectral properties are strongly modified by irradiation. In addition to the amorphization process, the remaining olivine lattice is highly strained due to the implantation of the incident ions. We suggest that the progressive shift of the MIR characteristics bands of olivine is due to lattice swelling related to the high concentration of interstitials species mostly coming from the implanted ions. Swelling in irradiated materials, including silicates, is a well-known process [e.g., 8-9]. The formation of gas nano-vesicles and the drastic change of density are likely the main cause of the modification of optical properties of the irradiated olivine.

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