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Laboratory simulations of space weathering and impact heating of planetary surfaces: the TEM studies.

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Introduction: Space weathering (SW) is alteration of optical and physical properties of the surface layers of airless solar system bodies due to exogenic processes such as micrometeorite bombardment and interaction with solar wind plasma. Understanding the nature of physical/chemical alteration produced by the SW processes is crucial to derive reliable mineralogical information from remote sensing data. Although natural space weathered samples collected from the surface of the Moon are available for study, the SW of other targets in different environments may produce different effects. Therefore, laboratory simulation experiments on various analogue materials and detailed characterisation of the produced effects are important.

Experiments: We plan to characterise SW effects on Mercury to determine to what extent they may affect the optical data from the BepiColombo Mercury Thermal Infrared Imaging Spectrometer (MERTIS) and other optical data from the BepiColombo and MESSENGER missions. Our results will also be important for understanding the SW effects on other airless solar system bodies. Using well-characterised Mercury analogue materials [1] and some additional relevant materials, two types of laboratory SW simulation experiments will be performed. The heating by micrometeorite impacts will be simulated by irradiation with pulse lasers [2, 3], while the effects of solar wind irradiation will be simulated by irradiation with low energy ions [4]. Earlier experiments [3, 7] and analysis of natural space weathered materials [5] have shown that nanophase Fe^0 ($npFe^0$) formed by reduction of Fe^{2+} plays an important role in the reddening of the optical spectra [6, 7]. However, minerals on Mercury surface are expected to be Fe-poor [8], therefore we plan to perform SW simulation experiments on Fe-free and Fe-poor silicate targets along with the Fe-rich ones, to assess the unique role Fe plays in space weathering. Optical alteration of the samples will be then analysed with VNIR reflectance and thermal IR emittance spectroscopy. Mineralogical, structural and textural modifications are keys to understanding the effects seen in optical spectra. To assess these factors, ATEM and HRTEM analysis of the artificially space weathered samples are underway.

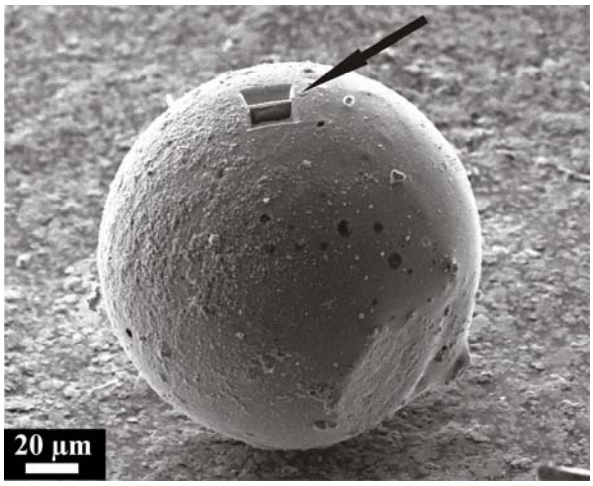

Fig. 1: SEM image of a FIB lamella prepared on an L-glass spherule.

Methods: For our initial study, we performed TEM analyses of artificially melted analogue materials of martian bright soil, which simulate the formation of impact glass on Mars [9]. These samples were used to test sample preparation and analytical techniques which we plan to apply to future analyses of artificially space weathered Mercury and other analogue materials. Three types of basaltic glasses were produced using pulse laser irradiation and melting in a resistance furnace [9, 10]. Glasses produced by pulsed laser irradiation are L-glasses, those produced by heating in a resistance furnace at 10^{-1} Hg pressure up to a temperature of ~1650ºC followed by slow cooling are S-glasses and glasses produced by heating at the same conditions, but followed by fast cooling are F-glasses [9, 10].
Sample preparation for TEM analysis of the resultant glass fragments and spherules was unsuccessful using conventional ultramicrotomy or ion-milling techniques. Ultimately, we used a Zeiss 1540 XB Focused Ion Beam-Scanning Electron Microscope (FIB-SEM) to cut a 15-20 µm long lamella (Fig. 1) from the glass. An area of ~7 x 10 μm^2 on the lamella was thinned to electron transparency, while the remaining portion of the lamella was not further thinned for better stability of the sample and for attachment to the copper grid. The FIB section was analysed using a Hitachi 800NA-TEM operated at 200 kV and a JEOL 3010 TEM operated at 297 kV.

Results: The SEM images of the dark and spectrally reddish S-samples were dominated by homogeneous glass, free of submicroscopic silicate crystals [9, 10]. Our TEM study, however, shows the presence of transparent crystals dispersed in the amorphous groundmass (Fig. 2). The bright field and dark field TEM image, as well as the diffraction pattern of the S-glasses obtained with the Hitachi TEM, showed that the glassy areas are completely amorphous. No metallic iron or iron oxide particles were found in the FIB section, which could have produced the darkening and reddening of the optical spectra of the S-glasses as documented in [10]. This observation supports the interpretation that the dark and reddish colour of the S-sample is due to dissolved Fe^{3+} in the glass. Fe^{3+} was detected by Mössbauer spectroscopy [10]. We also analysed an ion-milled TEM section of an S-glass fragment that contained silicate crystals (Fig. 2) dispersed in glass. Although the ion-milling had contaminated the amorphous areas, the crystalline material was, nevertheless, observed.

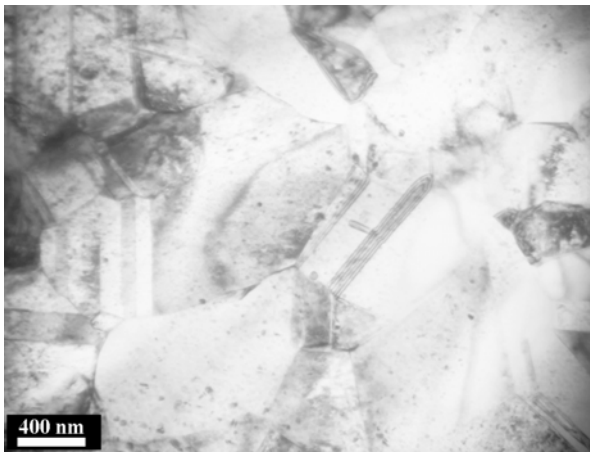

Fig. 2: TEM bright field image of crystalline silicate within the S-glasses.

Analysis of FIB sections of the F-glasses is not yet complete, but results similar to those for the S-glasses are expected since the Mössbauer spectroscopy of the F-glasses [9, 10] also showed high content of Fe^{3+}, which is the probable darkening and reddening agent in the S-glasses.

The dark field and bright field TEM images of the L-glasses (Fig. 3) showed the presence of numerous vesicles and spherical nanoparticles, ranging from 25-80 nm, dispersed randomly in an amorphous host material. The amorphous host is similar to that found in the S-glasses with respect to its appearance and diffraction pattern. The particles were too small to be identified using conventional SAED (Selected Area Electron Diffraction) or by CBED (Convergent Beam Electron Diffraction) diffraction techniques. HRTEM imaging of the particles is thus required to identify the particles and is currently underway.

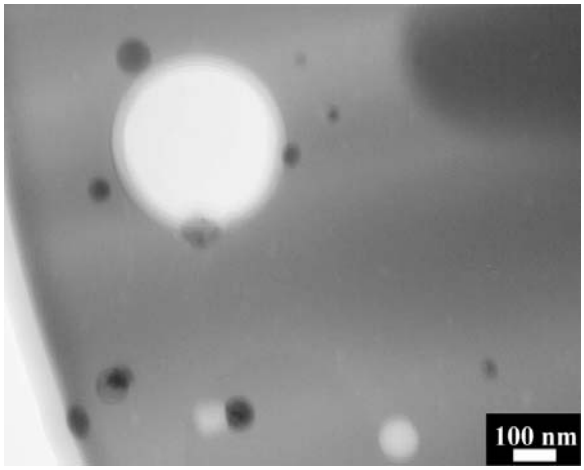

Fig. 3: TEM bright field image of the L-glass FIB lamella. The bright rounded objects are the vesicles.

Discussion: All the glasses produced in the experiment [9] showed darkening and reddening of the optical spectra [10]. Our TEM analysis indicated that Fe^{3+} dissolved in the amorphous part is the only darkening and reddening agent for the S-glass. The TEM imaging demonstrated that brighter and less red L-glass contains opaque crystalline nanoparticles whose identity is still to be verified using HRTEM. Since the L-glass does not contain Fe^{3+} [10], these particles are likely responsible for the darkening and mild reddening of the L-glass. If they turn out to be Fe^0, as suggested by Mössbauer spectroscopy [10] then we can demonstrate that nanophase Fe^0 can be produced by thermal reduction even without reducing conditions. This finding is important, since it would demonstrate that impact vapour deposition or ion-induced sputtering [11] are not the only mechanisms of $npFe^0$ formation for producing darkening and reddening on the airless solar system bodies. Impact melting due to micrometeorites and larger-scale impacts is expected to be significant in the Mercury environment and thus, we might expect similar thermally reduced $npFe^0$ in the hermian regolith, if the surface minerals contain enough Fe^{2+}.

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