Space Weathering-Related Evolution of Fine-Grained Asteroidal and Cometary Materials: An Implication for Sample Return Planetary Missions

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May 11, 2020

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Abstract— **The paper comprehends intends to make a summary of the multiple technological approaches to understand more about the mineralogy as well as the chemistry of the fine-grained astromaterials. Therefore, new aspects of non-destructive methods such as Scanning Electron Microscope-Cathodoluminescence and micro-Raman Spectroscopy are mentioned in the manuscript representing some advantages using those techniques in the Planetary Sciences, too. These techniques may also play a key role in future sample-return missions such as Osirix-Rex and Hayabusa-2.**

Keywords — education; planetology; geography; environment

I. Introduction

According to Britt et al [1], space weathering is a generic term for the effects on atmosphereless solid bodies in the solar system from a number of processes associated with direct exposure to the space environment. These include impact processes (shock, vaporization, fragmentation, heating, melting, and ejecta formation), radiation damage (from galactic and solar cosmic rays), solar wind effects (irradiation, ion implantation, and sputtering), and chemical reactions driven by these processes.

However, the space weathering mechanism of fine-grained astromaterials such as samples from the comet Wild-2 (Stardust-mission), the asteroid Itokawa (Hayabusa-mission), Interplanetary Dust Particles (IDPs), Calcium-Aluminium-rich Inclusions (CAIs) and micrometeorites have not been investigated in detail up to date. A better understanding of these processes can provide important insights into the formation of the solar system, protoplanetary disks, and planetary systems. For this purpose, efficient methods to study space weathering processes and their structural and chemical signatures in the selected samples are required.

Radiation effects on surface materials of the asteroid Itokawa were successfully studied by Micro-Raman spectroscopy, which revealed that ion implantation causes partial breaking of the crystalline or long-range order resulting in the production of radiation-induced defect centers in the albite as it was indicated by Kayama et al. [2] They observed that the Raman spectral features assigned to Si-O stretching vibrational modes decrease with rising radiation dose and ion implantation. Therefore, Micro-Raman spectroscopy has a big potential for the determination of cosmic radiation defects in the surface materials of the asteroid Itokawa. This can help to interpret the space weathering processes and formation history of asteroidal and cometary surfaces. Moreover, the same method can be applied to other fine-grained astromaterials such as Stardust particles, IDPs, meteorites, and micrometeorites.

Materials subjected to shockwaves display characteristic and irreversible physical and chemical changes on both macroscopic and microscopic scales, depending on the applied shock strength. Various techniques for the determination of the shock pressure or shock stage have been developed and applied for constituent minerals, in particular for feldspar (Langenhorst 2001-and references therein-[3]). However, these methods are not applicable to micrometer-sized particles composed of smaller grains. Moreover, according to Zolensky et al (2012-and references therein-[4]), shock metamorphism can reset chronologies in minerals, too. Therefore, a careful interpretation of the results obtained from the shock metamorphic studies is required to properly understand the shock wave history of our solar system.

Gucsik et al. [5] have used scanning electron microscope cathodoluminescence (SEM-CL) spectroscopy on the plagioclase-dominated RB-QD04-0022 Hayabusa sample containing a relatively high albitic content. They found that this sample was not affected by high-grade shock metamorphism. Furthermore, they also demonstrated that SEM-CL should be combined with micro-Raman spectroscopy in order to get more details on the space weathering processes.

II. METHODS

A. Micro-Raman Spectroscopy

Raman measurements are frequently used to study shifts of vibrational frequencies due to changes of bond lengths, which are coupled with the anharmonic nature of interatomic and inter-and intramolecular interactions. If a phase transition occurs, which ultimately depends on crystal and molecular symmetries, new characteristic spectral features will appear (e.g., [6]). Thus, this method is not only of great help in elucidating crystal structures, but can also be used as a method of qualitative analysis (fingerprinting) e.g., for determination of mineral phases up to a submicrometer scale without destroying them, and for quantitative measurements of shock and ion-induced weathering of planetary materials (Fig. 1). For many decades, Raman spectroscopy plays a major role in Planetary Sciences to identify the weathering and shock degree in meteorites and lunar rocks and to clarify the fluid-rock-atmosphere interactions and their mineralogical consequences on Mars, respectively. According to Bottger et al. [7] plagioclase grains from the Hayabusa samples has been identified using the Raman shifts around 477 and 510 cm^{-1} of the symmetric T-O stretching and the O-T-O deformation modes in the T-O groups (T can be K, Ca, Na) characterizing the feldspar. They also demonstrated that Micro-Raman spectroscopy would be a powerful technique in studies of specimens from fine-grained astromaterials.

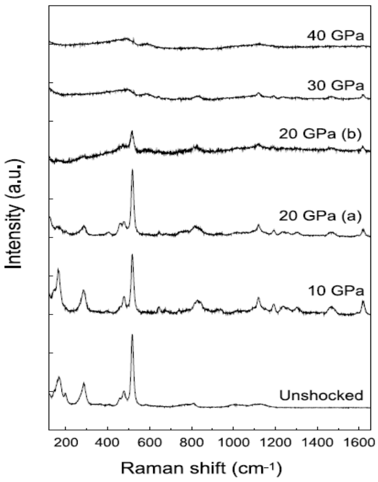

Figure 1. *Raman spectra measured for unshocked and experimentally shocked sanidine (from [8]; their Figure 2).*

B. Cathodoluminescence

Cathodoluminescence (CL) is the emission of photons in the visible range from a material stimulated by an incident electron beam, being feasible for high-spatial-resolution (~1 μm) spectroscopy. CL studies for minerals, especially feldspar, have been conducted in planetary sciences to characterize the shock metamorphic effect in samples to identify high-pressure minerals (e.g., [9]). Although these previous studies reported CL features closely related to shock metamorphism, quantitative information on the shock pressure have not been provided. These days, we can elucidate shock-induced effects on the CL spectra of alkali feldspars. Consequently, CL spectroscopy can be used as a universal shock barometer with high spatial resolution of ~1 μm in a wide pressure range from 4.5 GPa to >40 GPa (Kayama et al., 2012) (Fig. 2).

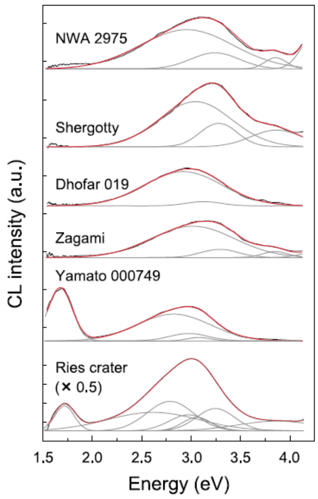

Figure 2. *Deconvoluted cathodoluminescence spectra of alkali feldspar in Martian meteorites and impactite (from [8]; their Figure 7).*

III. SHOCK PRESSURE ESTIMATION

Based on previous results on experimentally shocked feldspar, the shock pressures on fine-grained astromaterials are expected to be determined in a wide range between 4.5 and 40 GPa with an accuracy of 0.1 (Fig. 1) [8]. The shock estimation for plagioclase grains derived from Hayabusa using combined CL and micro-Raman analyses gives new insight into asteroid collision histories such as ejection from the parent body, aggregation to the present form, and formation of impact craters on the surface.

Recently, Micro-Raman analysis has been applied for a semiquantitative determination of shock stages in micrometer-ordered plagioclase or maskelynite grains in meteorites. Raman spectra of shocked plagioclase and maskelynite consist of peaks at 505 and 590 cm^{-1} attributed to the compression vibrations of the four-membered ring of tetrahedra [10]. The shock-induced deformation of the plagioclase crystal lattice causes a decrease in intensity and an increase in the luminescence background of these Raman peaks, which can be used as an indicator for the shock stage determination [8,11]. A multiple technological approach using Micro-Raman and cathodoluminescence spectroscopy enables us to obtain the best possible quantitative information about plagioclase particles from planetary materials that have suffered from a shock pressure treatment [11].

IV. EVALUATION OF RADIATION EFFECT

Micro-Raman spectroscopy can also reveal information about destructive, ion-induced, weathering processes of planetary materials. Ion implantation leads to characteristic structural changes along the penetration depth that can be clearly observed in minerals. Based on these measurements, the degree of weathering can be estimated quantitatively. Kayama et al. [2] demonstrated that He+ ion implantation causes a reduction of the intensity of Raman peaks assigned to Si-O stretching vibrational modes. The decrease in intensity was observed up to a depth of approximately 14 μm well corresponding to the results of CL measurements. The thickness of the destroyed area and the reduction of the Raman intensity can also provide information about the type of cosmic radiation and the deduction degree by space weathering, respectively. Using confocal Micro-Raman spectroscopy, important information of radiation-induced effects induced on plagioclase particles recovered not only from the Hayabusa project and but also from fine-grained astromaterials can be obtained without specific sample preparation, leading to a new understanding of the mechanism of space weathering of solar system materials.

V. APPLICATION

The combination of the Raman and Cathodoluminescence techniques provides us more understandings of the formation mechanism as well as shock wave physics of the planetary body such as comets and asteroids. It is also important to note that the data from the methods above would be used for the hyperspectral imaging systems of the planetary missions including the Hayabusa-2 (JAXA), Osiris-REX (NASA) as well as HERA (ESA), too. it will be interesting to analyse cathodoluminescence properties for presolar grains within interests of small bodies experiments in situ [12].

AKCNOWLEDMENT

Authors are very grateful for JAXA (Tokyo, Japan) providing some fine-grained astromaterials delivered from asteroid Itokawa.

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