Space weathering simulation of micrometeorite bombardment on silicates and their mixture for space application

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Abstract
Missions to planetary bodies require innovative techniques for the in situ investigation of their surfaces, especially when landings are planned. Therefore, Raman spectroscopy as an excellent laboratory tool for rapid mineralogical analysis of both terrestrial and extraterrestrial rocks has been successfully proposed for the investigation of planetary surfaces. Examples are the Raman laser spectrometer (RLS) of the joint ESA and Roscosmos mission ExoMars 2022 as well as Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) and SuperCam onboard NASA’s Mars2020 Perseverance Rover; another is the Raman spectrometer for Martian Moons eXploration (MMX) (RAX), which is being developed for the in situ exploration of the Mars’ moon Phobos. When preparing such space missions, it is essential to be prepared for all possible outcomes, such as samples exhibiting space weathering (SW). In this work, we study the influence of micrometeorite bombardment on bodies without atmosphere as one trigger of SW. This type of SW effect is simulated with an excimer laser irradiating the investigated samples with an energy density of \( \approx 2.5 \text{ J/cm}^2 \) for each pulse. As possible components on Phobos, we investigated the silicates olivine (Fo91) and pyroxene (En87) and their mixtures with Raman spectroscopy before and after laser irradiation. Surprisingly, the characteristic Raman bands of the individual minerals in the spectra are not influenced by this kind of SW. On the other hand, the fluorescence-dominated background signal induced by laser irradiation is reduced, possibly due to the formation of nanophase Fe, which then facilitates a better interpretation of the individual mineral peaks.

KEYWORDS
fluorescence, Raman spectroscopy, simulated micrometeorite bombardment, space missions, space weathering

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INTRODUCTION

Understanding the conditions under which planetary bodies in our solar system are formed is one of the goals of space missions in order to draw conclusions about earlier processes, for example, on Earth, Moon and other objects of the solar system. At best, in situ measurements of the mineralogy of these objects’ surfaces are possible. To realize this, in recent years, new instruments have been developed to study the surfaces and thus the mineralogy of the objects to be reached.

Raman spectroscopy does not require any sample preparation, and it belongs to the non-destructive spectroscopy methods. It is suitable to work under various environmental conditions, including vacuum. Therefore, it is an excellent tool to explore planetary surface materials in situ and is coming up for new space missions.

Two instruments that perform Raman measurements are located on the Mars2020 rover\textsuperscript{[1]} *Perseverance* that operates on Mars since February 2021—SuperCam and Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC). SuperCam performs remote time-resolved Raman measurements at 532-nm laser excitation to investigate targets up to 12-m distance from the rover, in order to provide information about the mineralogy and molecular structure of samples under consideration, as well as being able to search directly for organic materials. Beyond that, SuperCam includes other instruments like a red laser for remote analysis of chemistry by laser-induced breakdown spectroscopy. SHERLOC is an ultra-violet (UV) resonance Raman spectrometer for fine-scale induced breakdown spectroscopy. SHERLOC is an ultra-red laser for remote analysis of chemistry by laser-induced breakdown spectroscopy. SHERLOC is an ultra-red laser for remote analysis of chemistry by laser-induced breakdown spectroscopy.

In addition, the Raman laser spectrometer (RLS)\textsuperscript{[2]} on ExoMars 2022 is scheduled to be launched in autumn 2022. These instruments will be used on the surface of Mars to face the challenge of the search for signatures of past life and water and to investigate the composition of the surface that allows conclusions to be drawn about formation conditions. Comparable questions are the motivation for the Martian Moons eXploration (MMX\textsuperscript{[3]}), mission\textsuperscript{[3]} to be launched in 2024 to the Martian moons Phobos and Deimos\textsuperscript{[4]} with the new designed Raman spectrometer (Raman spectrometer for MMX [RAX]) on board. RAX was developed in an international collaboration between Germany, Spain and Japan\textsuperscript{[5]} and will investigate the minerals on the surface of Phobos in situ to answer the question about the moon’s origin and the circum-Mars material transport in more detail.

In order to optimize the development of those instruments and to interpret the expected data correctly, it is essential in preparation for such missions to investigate possible analogue materials including their alteration,\textsuperscript{[6–9]} because the obtained spectra are compared with existing databases on Earth.

On solar system bodies without atmosphere, the surface components are influenced by space weathering (SW).\textsuperscript{[10–12]} SW can be caused by factors such as heat- and pressure-related metamorphism and microparticle flux, solar flares and impacts of impactors various in size. As a product of SW, regolith is formed from the existing source rock by physical and chemical weathering, which consists mainly of silicate material. The loose and coagulated regolith material on the rocky planets and moons in our inner solar system is predominantly formed by impactors and high-energy radiation.\textsuperscript{[13]} Different factors of SW lead to various alteration processes on the surface and thus possibly to changes in the minerals, such as breaking molecular bonds, amorphization and forming of nanophase iron.\textsuperscript{[10,11,13]}

The objective of the present study is to investigate space-weathered rock-forming minerals with Raman spectroscopy in the scope of upcoming space missions. Of particular interest is micrometeorite bombardment as one source of SW, which is simulated with an excimer laser impinging the sample surface with an energy density of $\sim 2.5$ J/cm$^2$ in vacuum. Therefore, in the following, we use the term SW to describe the influence caused by micrometeorite bombardment only.

It is well known that SW influences infrared spectra from the near range to mid range.\textsuperscript{[14,15]} However, there is a lack of investigation dealing with the effect of SW on Raman spectra of rock-forming minerals. Although Matsuoka et al.\textsuperscript{[16]} studied the influence of low-energy laser irradiation on the Murchison CM chondrite with infrared and Raman spectroscopy, they only discussed the D and G bands of carbon measured with Raman spectroscopy. Brunetto et al.\textsuperscript{[17]} covered an equal field of interest. In their study, the ion irradiated impact and its influence on Raman spectra of carbon are of major interest. The attention on carbon is owed to the fact that the surface composition of, for example, Phobos and other objects in our solar system is assumed to be similar to carbonaceous chondrites, which contain a high amount of carbon.\textsuperscript{[18,19]} However, these objects also contain high amounts of silicates such as olivine, pyroxene and feldspar, which belong to the group of rock-forming minerals. Investigations of silicates modified by SW simulations with Raman spectroscopy are not yet known.

With this study, we will try to fill this gap for two important rock-forming minerals.

Here, we present the influence of micrometeorite bombardment on the silicates olivine (Fo$_{90}$) and pyroxene (En$_{87}$), as well as their mixtures. Forsterite (Fo) and enstatite (En) contents give the amount of Mg in the
structural formula of the minerals. These names correspond to the endmember of the minerals olivine and pyroxene, respectively. Forsterite is the pure Mg endmember of olivine, and enstatite is the pure Mg endmember of pyroxene. For the investigated minerals, this relates to the formulas: Mg$_{1.82}$Fe$_{0.18}$SiO$_4$ for olivine and Mg$_{1.72}$Fe$_{0.28}$Si$_2$O$_6$ for pyroxene.

Olivine shows Raman-active vibrational modes between ~180 and ~1000 cm$^{-1}$. The most characteristic peak of olivine is a double peak (DP), which appears because the two SiO$_4$ stretching ($\nu_1$ and $\nu_3$) modes are active, between ~815 and ~860 cm$^{-1}$ for Fe–Mg olivines.$^{[20]}$ Pyroxene shows Raman-active vibrational modes between ~220 and ~1050 cm$^{-1}$. The most characteristic Raman-active modes of pyroxene between 650 and 700 cm$^{-1}$ and between 1000 and 1050 cm$^{-1}$. In pyroxene, the vibrational modes are highly dependent on the symmetry (orthorhombic or monoclinic). The first ones between 650 and 700 cm$^{-1}$ are moderate Si–O–Si bending modes whereas the latter most prominent one from 1000 to 1050 cm$^{-1}$ belongs to the Si–O stretching mode.$^{[21]}$ On the basis of the different peak positions of the most prominent signals of these two minerals, we are able to distinguish between olivine and pyroxene in mineral mixtures.

For our investigations, we used pressed powder pellets to simulate the surface texture of regolith-covered bodies as closely as possible. Based on various preliminary tests, it was found that pressed powder samples are stable enough for laser irradiation to simulate SW. This is not the case with complete loose powder, as it was completely ejected from the sample container. However, the surface is again not completely dense, as is the case with stony bulk material or single crystalline minerals.

With our study, we try to solve the question whether or not micrometeorite bombardment as one source of SW will alter the Raman spectra of olivine and/or pyroxene. Such measurements are not yet available but are necessary for the interpretation of Raman spectra of future space missions.

2 | METHODS AND SAMPLES

2.1 | Methods

All Raman measurements were performed with a confocal Raman microscope WITec alpha300R system at DLR, Berlin. The Raman spectrometer operates with a laser excitation wavelength of 532 nm. The spectral resolution (pixel to pixel on the detector) is about 4 cm$^{-1}$. A Nikon 10× objective was used with a given spot size in focus on the pellets of about 1.5 μm. Spectra were taken at 3 mW, which then equals to 1.7-mW/μm$^2$ laser irradiation on the sample, to reflect the conditions of RLS and RAX. The investigated area was a 1000 × 1000 μm$^2$ field scanned with 50 × 50 points, which gives 2500 spectra per sample. The integration time per spectrum was 2 s. Although the short time per spectrum results in a low signal-to-noise ratio, it is sufficient to derive a statistical statement of the natural behaviour of the fluorescence from a large number of spectra in a reasonable time. In addition, due to the roughness of the sample pellets, it is necessary to work statistically and with a medium focus, which leads to a variation in the signal-to-noise ratio of the spectra, but this has no effect on the interpretation of the Raman bands of the respective mineral. To find the Raman line peak position for an exact data interpretation, a peak fit to all Raman lines of interest using the evaluation software of the WITec System was applied. This includes a background subtraction of dark current and fluorescence and a Gaussian fit as part of this evaluation software.

The laser irradiation for SW simulation was done with an excimer laser system (ArF UV laser; wavelength 193 nm) LPX120i (Lambda Physik AG [Coherent Inc. USA]) at the Physikalisches Institut, Münster. A high vacuum chamber was necessary to simulate the environmental conditions corresponding to those of planetary bodies without atmosphere. We used a redesigned Praying Mantis™ High Temperature Reaction Chamber, which enables pressures down to at least 10$^{-4}$ Pa. For the chamber, a new dome was constructed for a simultaneous use of the chamber for laser irradiation and subsequent infrared measurements before and after irradiation (the results of the IR measurements are not part of this paper). We positioned the laser in front of a laser-transparent MgF$_2$ window at the top of the dome. Once the laser beam passed the window, it hit the sample surface. To protect the sealing ring, we used a cover ring on top of the MgF$_2$ window.

The pressed powder pellets were irradiated with three laser shots per point, and the energy density was determined with ~2.5 J/cm$^2$ over the entire area. The laser beam focus point was approximately 250 × 500 μm$^2$. The central area of the laser beam focus point was approximately 100 × 200 μm$^2$, which was decisive for the bombardment point density. The bombardment points were varied in y and x directions. The entire chamber was moved manually in discrete steps under the laser beam to achieve complete coverage of a maximum area of the sample surface with laser irradiation. An example of a scanned irradiated and nonirradiated surface is given in Figure 1a–d.

Mineralogical investigations were done using a JEOL JXA-8530F Hyperprobe electron probe microanalyser.
(EPMA) at the Institute of Mineralogy, Münster, equipped with four wavelength-dispersive spectrometers. An excitation voltage of 15 kV and a beam current of 15 nA were used. Natural and synthetic standards of well-known compositions were applied, and corrections for matrix effects were made with the Φρ(2) procedure.

2.2 Sample characterization and preparation

For this study, two iron-poor natural silicates, an olivine (Ol = Fo91) from Dreyser Weiher, Germany, and a low Ca pyroxene (Px = En87) from Bamble, Norway, were used as expected rock-forming minerals for most planetary bodies. Due to the natural nature of the samples, these are not pure mineral separates. The powder of olivine contained ~8 vol.% pyroxene and phyllosilicates, whereas the pyroxene itself was serpentinized of up to 10% by volume.

The minerals were pulverized with a steel mortar, before pellet pressing. For subsequent infrared analyses, the powder was separated in different grain size fractions. For pellet pressing, the grain size fraction from 63 to 125 μm was used (Figure 2a). The diameter and height of the compact sample pellet was limited to d = 6 mm and

FIGURE 1 Images of the olivine pellet surfaces (a,c) before and (b,d) after the laser irradiation done with a KEYENCE Digital Microscope. A close-up image is given in (e) before (top) and after (below) irradiation done with the WITec microscope. The 3D image (b) has an irradiated dark, flattened surface, compared with the raw surface in (a). On the irradiated dark surface (d), the central area of the laser beam focus point can be seen as black points.

FIGURE 2 Images of olivine grain size fraction done with a KEYENCE Digital Microscope. (a) Grain size fraction from 63 to 125 μm before the pressing process. (b) Grain size fraction of the powder after the pressing process.
h = ∼3 mm, respectively, by the size of the sample holder in the vacuum chamber. The pellets were pressed in a hydraulic press with approximately 20 kN for 25 min to get stable pellets, which were still a bit loose on the surface. The sample grain size range was smaller than 125 μm after pressing (Figure 2b). The samples were monitored with a KEYENCE Digital Microscope VHX-500F at the Institut für Planetologie (IfP), Münster, before and after laser irradiation (Figure 1).

Studies were performed on natural olivine and pyroxene separates and on a mineral mixture of both with different ratios (100 wt.% olivine, 50 wt.% Ol/50 wt.% Px, 30 wt.% Ol/70 wt.% Px, 15 wt.% Ol/85 wt.% Px and 100 wt.% pyroxene).

3 | RESULTS

As a result of pellet pressing, we see that the size distribution of the minerals has changed. Now, minerals are present in sizes from 1 to ∼100 μm (Figure 2a,b). This size distribution is very close to typical regolith sizes[22] expected on solar system objects without atmosphere. Images of the sample surfaces before and after laser irradiation show a clear darkening of the irradiated sample compared with the fresh one (Figure 2a–d). A slight flattening of the surface in Figure 2b and the formation of an irradiation ‘hill’, most likely the ejecta from the impact of the laser pulse, around the irradiated area are also visible.

The Raman spectra of the nonirradiated olivine separates in the range from 200 to 1200 cm⁻¹ show typical Raman wavenumbers of the mineral-type DP at about 826/857 cm⁻¹ and smaller peaks at 921 and 965 cm⁻¹ (Figure 3, bottom spectrum).

The low Ca pyroxene separates reveal Raman wavenumbers characteristic for the mineral at around 341 cm⁻¹, a DP at 669/686 cm⁻¹ and a Raman wavenumber at 1014 cm⁻¹ (Figure 3, middle spectrum) in the range from 200 to 1200 cm⁻¹. Mineral mixtures result accordingly in a mixture of both spectra (Figure 3, top spectrum).

Surprisingly, the studies in the irradiated region of the mineral separates show the same Raman spectra as those of the nonirradiated ones. Within the error (compare Section 2.1), which is smaller than 4 rel. cm⁻¹ due to averaging over 2500 spectra, the position of the typical Raman wavenumbers does not change. Figure 4 show the single spectra of the minerals after irradiation. Olivine (Figure 4, bottom) can be identified by the DP at 826 and 857 cm⁻¹. Pyroxene (Figure 4, top) can be determined by its peaks at 341 cm⁻¹, the DP at 668/686 cm⁻¹ and the strongest peak at 1014 cm⁻¹. A mixture spectrum (Figure 4, middle) shows all peaks of both minerals.

The typical mineral Raman peaks itself did not change their position, and thus, the minerals did not alter on the Raman scale with laser irradiation simulating micrometeorite bombardment.

On the other hand, the fluorescence, present in almost all spectra, is affected by this irradiation, which is already visible by comparing the Raman intensity in Figures 3 and 4 with each other. In these figures, it can be seen that the fluorescence in the olivine spectra is low compared with the pyroxene spectra and the mixture of

**FIGURE 3** Averaged (2500) Raman spectra of the nonirradiated samples in the range from 200 to 1200 cm⁻¹. Bottom: spectrum of olivine, which can be identified by the typical double peak (DP) at 826/857 cm⁻¹. Middle: spectrum of low Ca pyroxene, which can be identified by the typical Raman wavenumbers at 341 cm⁻¹, the DP Raman wavenumbers at 669/686 cm⁻¹ and the Raman wavenumber at 1014 cm⁻¹. Top: spectrum of a mixture of olivine and low Ca pyroxene. The typical shifts of both are marked by arrows. The Raman intensity scale is the same for all three spectra, no offset is applied.
both. The statistically averaged fluorescence of the olivine/pyroxene mixture decreases significantly after irradiation, whereas the fluorescence of pyroxene remains high. It should be mentioned that all samples and spectra were treated under the same experimental conditions and were measured with the same Raman settings as described in Section 2.1.

Statistically high fluorescence levels of the non-irradiated samples (Figure 5) are reduced by the laser irradiation simulating the micrometeorite bombardment. The maximum fluorescence values of all 2500 spectra of one sample are excised, and the overall fluorescence of all spectra of one sample is reduced on irradiated compared with the nonirradiated samples. Comparative fluorescence histograms of nonirradiated and irradiated samples demonstrate this effect. In Figure 5, the histograms of the background of the spectra of samples containing olivine, pyroxene and mixtures are shown. The histograms show the background intensity distribution represented by charge-coupled device (CCD) counts on the abscissa in Figure 5 derived from 2500 spectra taken at 50 × 50 points on each sample. The background includes the instrument specific almost constant dark current and the sample dependent fluorescence. For the histogram calculation, the spectral region at 1400 cm\(^{-1}\) with a width of 40 cm\(^{-1}\) was chosen as there are no mineral-specific Raman lines. Here, the intensity variation of the spectrum is fully determined by fluorescence. Each column in a histogram represents the number of spectra (of 2500 spectra for one sample) having a certain intensity (in CCD counts) in the spectral range from 1380 to 1420 cm\(^{-1}\). The number of columns (bins) of each histogram equals 100. The intensity in this spectral range is derived from each of the 2500 spectra from 50 × 50 points on each sample.

As a further result worth mentioning, although not directly correlated to the topic of the paper, we found a phyllosilicate and a spinel in one of the mineral separates (Figure S1), which demonstrates the natural origin of the used minerals and the possibility to identify also trace minerals. The Raman spectrum allows the identification of an antigorite, which is a type of serpentine with the structural formula of \(\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4\), with typical Raman wavenumbers at 220, 370/395 and 675 cm\(^{-1}\).\(^{[23]}\) The second one is a magnesium ferrite spinel with typical Raman wavenumbers at 600 and 720 cm\(^{-1}\).\(^{[24]}\) Because these are trace minerals and not detectable in all sample pellets, no comparison of the fluorescence was done.

4 | DISCUSSION

With the implementation of Raman spectroscopy on space mission landers, like the above-mentioned new Raman spectrometer RAX to study the Mars’ moon Phobos, it is increasingly important to perform laboratory studies with possible analogue materials to better interpret the expected data. In terms of analogue materials, it is essential to think about all possible scenarios that could have taken place on the body being examined and have formed the surface we are studying at the moment of landing. Bodies of the solar system without atmosphere are, after their formation and beside possible
inner geological processes (e.g., weathering by water),
defencelessly exposed to SW. One source of SW is the
continuous micrometeorite impact that we have simu-
lated within this study.

As already known from other investigations,[25] we
can confirm a darkening of all laser-irradiated surfaces,
which is already visible to the naked eye in the visible
wavelength range. This kind of visible darkening of the
surface is related to the local temperature increase that
occurs due to the laser bombardment. It is expected that,
corresponding to investigations done by Loeffler et al.[26]
with an equal experimental set-up, a very thin and small
part of the surface melts for a short time, agglutinates
and recrystallizes directly (Figure 1e). Because the laser
area of about $250 \times 500 \mu m^2$ is larger than the largest
mineral grain present, we assume that these grains
agglutinate at the surface. An extremely thin nanometre
layer remains in glassy structure. The laser bombard-
ment is an extremely fast process of nanoseconds. In
addition, when rock-forming silicates irradiated in the
laboratory were evaluated by ultraviolet-visible (UV/VIS)
and near-infrared (NIR) spectroscopy, which is widely
used in remote sensing, especially for space missions, it
was found that the spectra of irradiated samples show a
lower intensity of the spectra compared with the non-
irradiated ones.[26] This is consistent with real remote
sensing data, which so far have provided spectra with
rather low intensity.[27] One possible explanation of those
darkening is the formation of nanophase iron.[28] These
iron particles occur in silicates that have Fe in their
structural formula. Even if there is little Fe, such as in
the forsterite with Fo$_{91}$, a rather Mg-rich olivine that we
studied, nanophase iron particles can form.[26,29] In these
studies, for the Bamble pyroxene and for a forsterite,
with composition and structure equivalent to the one
used in our study, the formation of nanophase iron is
proved by the same (Ol) or similar (Px) laser experi-
ments.[26,29] Studies via transmission electron microscopy
(TEM) of those samples and of lunar regolith show the
formation and existence of nanophase iron particle in
various sizes. However, due to the small size of these
particles, with only about up to $\sim 30$ nm, so far, only
TEM analyses are feasible to detect these tiny units[30]
that are embedded in the pristine silicate or in an

![Figure 5](image-url)
amorphous silicate matrix. TEM investigations also show that the nanophase iron is always covered by a ∼100-nm-thick glassy material.\(^{[29,30]}\) The glassy amorphous material consists mostly of the former silicate. These original silicates are still present and unchanged under the amorphous layers of space-weathered material. This is consistent with our results of the irradiated surfaces investigated by Raman spectroscopy. All mineral separates show the same spectra before and after irradiation. No hints for an amorphous surface are visible. The penetration depth of Raman spectroscopy is extremely dependent on the wavelength applied, as well as the mineral studied. However, the penetration depth is in the range of several micrometres compared with the only few nanometres thick\(^{[31]}\) glassy layer as remnants of the irradiation for olivine and pyroxene. Those glassy layers are also known from the regolith on the Moon and from the Itokawa asteroid (Keller and Berger\(^{[32]}\) and references therein). Pure iron is not Raman active and cannot be measured by Raman spectroscopy. The spot area of our Raman microscope is 2.5 \(\mu m^2\), which is much larger than the size of assumed iron particles. But although we cannot resolve the nanophase iron particles, the change in the fluorescence background in the Raman spectra can be a hint of their existence. One explanation and hypothesis, that must be proven and is beyond the scope of this paper, is that the fluorescence is based on an excess of freely available electrons in the conduction band that relax into the vibrational or ground state by excitation with Raman laser. Some of these electrons can be captured/bounded by the above-described nanophase Fe and are no more available for fluorescence processes if Raman laser excitation takes place. In this case, the fluorescence level decreases, especially, when it was high for nonirradiated samples. This can be seen in a shift of the maximum in the histograms in Figure 5 to lower Raman intensity (in CCD counts) values for irradiated samples compared with nonirradiated. In addition, the histogram shifts overall to lower values and describes that high fluorescence values disappear. This is especially applicable when high fluorescence values are available for nonirradiated samples (Px/Ol mixtures, Figure 5).

Furthermore, the agglutination might reduce the overall fluorescence of the surfaces itself. Due to the amorphization of the upper part of the slightly loose surface, the very tiny particles disappear in favour of a slightly flatter surface. The Raman laser irradiation is multiple scattered on a rough surface and is better focused on a flatter surface. No disturbing grain multiple scattering is visible after agglutination.

Another noteworthy find was the phyllosilicate and the spinel in one of the mineral separates. These minerals were found by random while scanning the surface. Even though the amount of other side minerals in the selected minerals was low, Raman spectroscopy was able to find this tiny spot in mineral mixture. Raman bands can be used to identify the phyllosilicate without any doubt. This is promising, because it proves once more the necessity of Raman spectrometers on space missions as already suggested by Haskin et al.\(^{[33]}\) because these enable the identification of minerals and trace minerals in one measurement sequence by their specific Raman wavenumber positions.

5 | SUMMARY AND CONCLUSION

The main aim of our study was to investigate whether or not Raman spectra are sensitive to micrometeorite bombardment as one source of SW. We found that Raman spectroscopy is able to investigate the pristine surface of a planetary body very well. Because of the penetration depth of the Raman laser, Raman spectroscopy will not be suitable to distinguish between a micrometeorite-bombarded surface and a fresh surface. However, the investigated solar system body is bombarded and redistributed since its formation. Therefore, the affected material might be deeper below the surface of the studied body itself. To study this, further work is planned on more gardened samples. From the laboratory measurements, it can be expected that micrometeorite bombardment as a source of SW could reduce the overall fluorescence on the surface. But independently from fresh or weathered material, Raman is an appropriate tool to analyse the pristine surface, as the weathered surface is only a few nanometres thick. Furthermore, Raman spectroscopy enables the detection of two or more minerals in only one measurement sequence. Therefore, Raman spectroscopy once again turned out as an excellent instrument for space missions.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.