

Detection of solar wind-produced water in irradiated rims on silicate minerals

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The solar wind (SW), composed of predominantly ~1-keV H⁺ ions, produces amorphous rims up to ~150 nm thick on the surfaces of minerals exposed in space. Silicates with amorphous rims are observed on interplanetary dust particles and on lunar and asteroid soil regolith grains. Implanted H⁺ may react with oxygen in the minerals to form trace amounts of hydroxyl (–OH) and/or water (H₂O). Previous studies have detected hydroxyl in lunar soils, but its chemical state, physical location in the soils, and source(s) are debated. If –OH or H₂O is generated in rims on silicate grains, there are important implications for the origins of water in the solar system and other astrophysical environments. By exploiting the high spatial resolution of transmission electron microscopy and valence electron energy-loss spectroscopy, we detect water sealed in vesicles within amorphous rims produced by SW irradiation of silicate mineral grains on the exterior surfaces of interplanetary dust particles. Our findings establish that water is a byproduct of SW space weathering. We conclude, on the basis of the pervasiveness of the SW and silicate materials, that the production of radiolytic SW water on airless bodies is a ubiquitous process throughout the solar system.

solar wind radiolysis | prebiotic water | cosmic dust | astrobiology | aberration-corrected scanning transmission electron microscopy

There are two principal space weathering processes, solar wind (SW) ion irradiation and micrometeorite impacts, that produce rims on exposed mineral surfaces (1). Our focus here is on SW irradiation because of its possible connection to the production of water and hydroxyl radicals (2–5). Space-weathered rim thicknesses vary with the densities of implanted solar flare (SF) tracks, and track densities depend on the exposure ages of individual interplanetary dust particles (IDPs) in space. On lunar soil grains and grains on surfaces of IDPs, rims are typically 75–150 nm thick with SF track densities of 10^{10} – 10^{11} cm^{–2} that are consistent with 10^4 - to 10^5 -y SW exposure ages (6, 7) (Fig. 1 B–D). Rims on asteroid Itokawa regolith grains are 30–60 nm thick with SF track densities of 5×10^9 cm^{–2} that are consistent with $\sim 10^3$ -y exposure ages (8) (*Origins and Properties of Rims on IDPs, Asteroid Itokawa, and Lunar Soil Grains*). This correlation between amorphous rim thicknesses and SF track densities indicates that SW irradiation is the primary mechanism for amorphous rim formation. We examine rims on surface grains in IDPs because they are solely due to SW irradiation, whereas rims on lunar soil grains are due to SW irradiation, impact vapor deposition, or a combination of both (9), and remote observations suggest that if water is indeed produced in rims on lunar soil grains, it is not efficiently retained (10). Typical 5- to 25- μ m diameter chondritic porous (CP) IDPs are low-density aggregates of predominantly submicrometer-sized grains, and they are collected in the stratosphere (11) (Fig. 1 A–D and *Origins of CP IDPs*). Chemical analyses of the rims on silicate grains at the surfaces of IDPs reveal that SW sputtering breaks atomic bonds and selectively removes cations (e.g., Mg), leaving a stoichiometric excess of oxygen and

rendering the rims chemically reactive. Similar cation depletions and oxygen excesses are observed in amorphous rims produced during laboratory irradiation of crystalline silicate standards using H⁺ and He⁺ ions at SW fluences (12).*

Previous attempts to detect water in rims on the surfaces of irradiated oxygen-rich minerals using bulk analytical methods, where water, if present, is close to detection limits, have yielded conflicting results (13, 14). We used valence electron energy-loss spectroscopy (VEELS) because its ability to detect water in situ at the nanoscale has been demonstrated in aqueous liquids, biomaterials, and ices (15–17). VEELS characterizes the low-loss region of the energy loss spectrum (0–50 eV), where features due to plasmons, valence band transitions, –OH, and H₂O can be observed (12, 15–19). We detect water in the SW amorphous rims on nominally anhydrous CP IDPs. To confirm this identification and to evaluate the VEEL spectra water features as a function of local solid-state environment and incident electron dose, we compare our results from the IDPs with three sets of standards: man-made liquid cells, empty and water-filled (20); talc, a hydrous mineral [Mg₃Si₄O₁₀(OH)₂]; and H⁺- and He⁺-irradiated anhydrous silicates (a description of the liquid cell is provided in *Materials and Methods*).

Results

VEEL spectra from the empty and water-filled liquid cells and talc are compared in Fig. 2 A–C. The spectrum from the empty cell contains a single feature peaked at 23 eV, the volume plasmon,

Significance

Whether water is produced by solar wind (SW) radiolysis has been debated for more than four decades. In this paper, we exploit the high spatial resolution of electron microscopy and sensitivity of valence electron energy-loss spectroscopy to detect water (liquid or vapor) in vesicles within (SW-produced) space-weathered rims on interplanetary dust particle (IDP) surfaces. Water in the rims has implications for the origin of water on airless bodies like the Moon and asteroids, the delivery of water to the surfaces of terrestrial planets, and the production of water in other astrophysical environments. In particular, water and organic carbon were likely delivered simultaneously by the high flux of IDPs accreted by the early Earth and other terrestrial planets.

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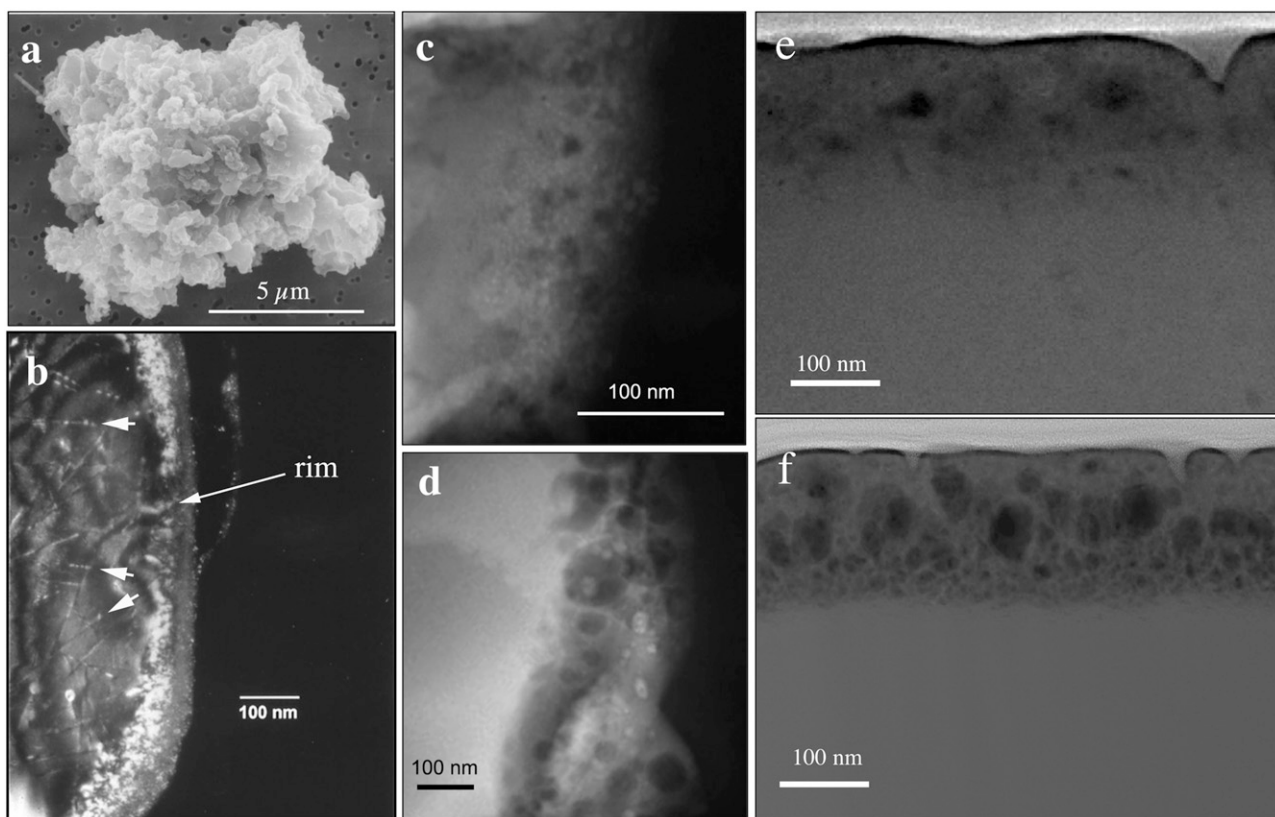


Fig. 1. (A) Secondary electron image of CP IDP U220A19. (B) Dark-field image of a pyroxene crystal on the surface of U220A19 with an ~ 100 -nm thick amorphous rim resulting from SW irradiation. The linear features (arrows) in the pyroxene crystal are SF tracks. (C) High-angle annular dark-field (HAADF) density contrast image of the SW rim on the pyroxene showing vesicles within the amorphous silicate rim. (D) HAADF image of a vesiculated rim on a lunar soil anorthite crystal. Water was not detected in the vesicles. HAADF images of the amorphous rims on the surfaces of olivine (E) and anorthite (F) crystals following exposure to 5-keV He^+ (7.5×10^{18} He^+ per square centimeter) and 5-keV H^+ (1.0×10^{19} H^+ per square centimeter), respectively.

that is directly related to the specimen dielectric function (18). With water in the cell, a feature appears at 8.5 eV, and a second feature at 13.5 eV with fine structure extending to ~ 16 eV is sometimes observed. Depending on specimen thickness, a much weaker and broader third feature at 4.3 eV is observed. The 4.3-eV feature corresponds to the ionization threshold (IT) of water, the 8.5-eV feature corresponds to the energy gap (EG) of water, and the 13.5-eV feature is the hydrogen (H-K) core scattering edge (15–17, 21, 22).

Talc is thermally sensitive like other hydrated layer-lattice silicates that contain structurally bound water, and it decomposes in the electron beam to form enstatite (MgSiO_3), silica (SiO_2), and unbound water (H_2O) (23). Using VEELS, we monitored unbound water accumulation as a function of electron dose (Fig. 2 D–F). At low beam currents (0.05 nA), no water features are evident, but as the current is increased, both the IT and H-K edge features appear in conjunction with visible bubbling (rapid vesicle growth). A similar dependence of water features on electron dose and bubbling is observed when water ice is melted in the electron beam (16, 17).

The laboratory-irradiated anhydrous silicate mineral standards are olivine ($[\text{Mg,Fe}]_2\text{SiO}_4$), clinopyroxene ($[\text{Ca,Mg,Fe}]\text{SiO}_3$), and anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) (*Materials and Methods* and *SI Materials and Methods*). Both H^+ - and He^+ -irradiated standards have ~ 100 -nm thick amorphous rims on their surfaces that contain vesicles 10–50 nm in diameter (Fig. 1 E and F). VEEL spectra from the rims differ from those from underlying mineral substrates (Fig. 2 G–J). The substrate spectra have relatively narrow volume plasmon peaks, typical of crystalline silicates, with weak surface plasmons between 8 eV and 12 eV originating from the upper and

lower surfaces of the thin specimen. The volume plasmon peaks from the rims are significantly broader and are often shifted to a lower energy because surface plasmon contributions are greater due to irradiation-induced atomic-bond disruption, the presence of vesicles, and nanoporosity (12, 18, 19). Water IT, EG, and H-K features are observed in some vesicles in H^+ -irradiated rims but not in He^+ -irradiated rims, where, instead, the He-K core scattering edge at ~ 22 eV is observed in some vesicles (Fig. 2 G–J). A higher abundance of water-bearing vesicles was noted in the irradiated anorthite standard relative to the pyroxene and olivine standards.

VEEL spectra water features are similarly detected in amorphous rims and in vesicles contained within the rims on silicate grains in several CP IDPs (*Materials and Methods* and *SI Materials and Methods*). Fig. 3 A–C shows successive spectra from a vesicle at the base of the rim on a pyroxene crystal in CP IDP U220A19. Water IT, EG, and H-K features remain prominent until the electron beam perforates the vesicle, and they abruptly disappear as water escapes to vacuum. Spectra from the rim exhibit IT and EG features, and the pyroxene crystal exhibits only weak surface plasmons (Fig. 3 D and E). Relative to the spectrum from the pyroxene crystal, the rim spectra have a significantly broader plasmon peak shifted downward in energy by ~ 2 eV. A vesicle in the rim on another IDP (U2001 D7) exhibits IT, EG, and double-peaked H-K features, and the amorphous rim alongside the vesicle exhibits an IT feature (Fig. 3 F and G). We estimated the abundance of water in rims by X-ray energy dispersion spectroscopy (EDS) quantification of elemental abundances. Some SW rims on IDPs have up to 12 atomic percent excess O relative to oxide stoichiometry, attributable to, at most, ~ 1 weight percent water in the rims (*SI Materials and Methods*).

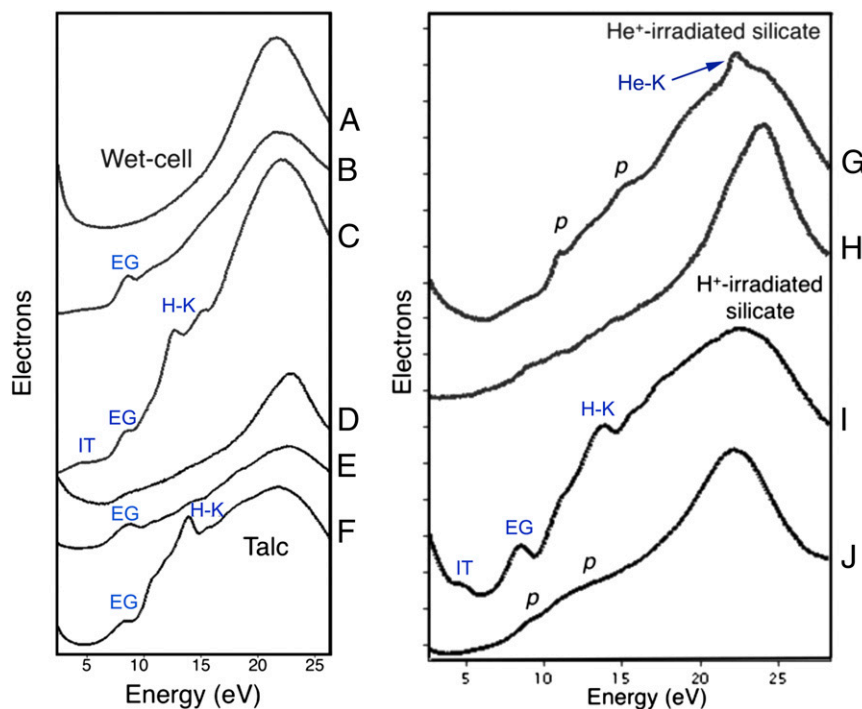


Fig. 2. VEEL spectra from an empty liquid cell (A) and two different locations in the water-filled cell (B and C). VEEL spectra from talc acquired over a constant time interval using a beam current of 0.05 nA (D), 0.15 nA (E), and 0.25 nA (F) are shown. (G and H) VEEL spectra from He⁺-irradiated rim and olivine substrate. (I and J) Spectra from H⁺-irradiated rim and anorthite substrate. IT, water IT; H-K, H-K core edge; p, surface plasmons. The beam current is ~0.05 nA for G–I. Details of mineral irradiation by He⁺ and H⁺ are provided in *SI Materials and Methods*.

Discussion

We find that detection of structurally unbound water in minerals using VEELS depends on the local physical environment of the water and incident electron dose. In a liquid cell, where water is not laterally confined, the position of the EG feature varies from 8 to 9 eV and the H-K feature may or may not be observed (15) (Fig. 2A–C). With talc, the appearance of these features depends on electron dose and bubble formation, similar to water ice (Fig. 2D–F). With water sealed in vesicles in SW rims, IT, EG, and H-K features are often immediately apparent even at low electron doses (e.g., Fig. 3A and B). Prior studies of the VEEL spectra from liquid water and their degradation byproducts are sparse: Water dissociates in the electron beam, forming transient species that include H⁺, O[•], OH[•], H[•], H₂, H₂O₂, and HO₂[•] (15–17). VEELS of molecular oxygen and hydrogen, which exhibit features at 13 eV and 15 eV, respectively, show that these peak positions are perturbed by formation of other stable molecules (e.g., CO, CO₂), which leads to an increase in the binding energy due to charge screening of the positive oxygen core (24). We attribute variations in the VEEL spectra water features to similar effects because, in addition to water, the rims and vesicles almost certainly contain Si-OH and possibly other species (e.g., carbon compounds) that were recoil-implanted into the rims by the SW.

Our detection of SW-produced water in rims on silicate mineral grains in nominally anhydrous IDPs has implications for production of water on the surfaces of airless bodies, its delivery to the surface of the Earth and other terrestrial planets, and production of water in the interstellar medium (3–5, 13).[†] For example, there is intense interest in water at the poles of the Moon (10, 25–27). A fundamental and as-yet unresolved question is the source of the water. Three sources have been proposed

(i) primordial water present when the Moon formed and now sequestered in the lunar regolith, (ii) impacts by ice-rich comets and wet asteroids, and (iii) in situ water formation on the surfaces of oxygen-rich lunar mineral grains exposed to SW H⁺ (1–3, 10, 25, 26). The sample analyses presented here, together with remotely sensed observations (10, 26), yield supporting evidence for the in situ creation of OH/H₂O by SW radiolysis of the lunar regolith. Previous sample studies have described the mechanism by which the SW could produce hydroxyl in the lunar regolith (5, 25). This study establishes that the SW does produce water in rims on silicate minerals. Although the VEELS data presented here are from CP IDPs, silicates and SW are common to both the Moon and asteroids. Hence, we infer that a similar process of creation of water must be occurring on these airless bodies, consistent with both our experimental findings and the lunar remote-sensing data. For example, anorthite is the most oxygen-rich of the silicates we examined, and we observed the highest abundance of vesicles with detectable water in the H⁺-irradiated rim on the anorthite standard. The Moon-mineralogy imaging spectrometer detected the strongest hydroxyl absorption features associated with fresh craters in the anorthite-rich lunar highlands (26).

Although the remote observational data and our IDP sample analysis provide compelling evidence that the SW produces lunar water, detecting it in rims on lunar grains is expected to be challenging. Apart from at least two processes implicated in lunar rim formation (9), remote spectral data from the National Aeronautics and Space Administration’s EPOXI mission (10) reveal a dynamic diurnal process of hydration, dehydration, and rehydration of the lunar regolith as a function of surface temperature that exceeds 100 °C in midlatitude regions. Typical CP IDPs, on the other hand, are from small frozen (cometary) parent bodies, and they can remain cold (≤10 °C) during their 10⁴- to 10⁵-y exposures to the SW while in solar orbit. They are pulse-heated for several seconds during entry, but the survival of

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