Introduction: Space weathering processes such as micrometeorite bombardment and solar wind irradiation alter the microstructural, compositional, and optical properties of airless body regolith. Space weathering complicates the interpretation of remote sensing data and the subsequent characterization of airless surfaces, making it a primary concern for the Hayabusa2 and OSIRIS-REx missions which will soon return samples from C-complex asteroids Ryugu and Bennu, respectively [1,2,3]. To improve our understanding of the effects of space weathering on hydrated, organic-rich materials, maximize scientific return from remote sensing data, and prepare for the analysis of returned samples from these missions, we simulated solar wind exposure on CM2 Murchison—a suitable analog for C-complex asteroids [4]—in the laboratory. Here, we present results from a coordinated analysis investigating how the microstructure, chemistry, and spectral properties of carbonaceous chondrites are modified by 1 keV/amu He* and H* ion irradiation.

Methods: He* and H* ion irradiation were performed separately under ultra-high vacuum on two discrete 6x6 mm regions of a dry-cut Murchison slice. An electron neutralizer was operated simultaneously with irradiation to maintain surface potential, and a Faraday cup measured ion flux before and after irradiation. Using a flux of 1.1x10^13 ions/cm²/s, the first region was irradiated with 4 keV He* to a total fluence of 1.1x10^18 ions/cm² (~6000 years of exposure at Bennu) while the second region was irradiated with 1 keV H* to a total fluence of 8.1x10^17 ions/cm² (~200 years of exposure at Bennu). To comprehensively analyze irradiation-induced modifications in the sample, we employed four analytical techniques: X-ray photoelectron spectroscopy (XPS), visible to near infrared (VNIR; 0.35 – 2.50 μm) spectroscopy, two-step laser-desorption mass spectrometry (μL²MS), and transmission electron microscopy (TEM). We employed changes in surface chemistry using an X-ray Photoelectron Spectrometer (XPS; PHI Versaprobe) with a monochromatic, scanning X-ray source (AlKα: 1486.7 eV) and hemispherical electron-energy analyzer. Survey spectra (wide scan) were obtained from He*- and H*-irradiated matrix- and chondrule-bearing regions. High-resolution spectra (narrow scan) were acquired from the H*-irradiation experiment only. VNIR spectra collected using a fiber-optic ASD FieldSpec 3 Spectrometer (Malvern Panalytical) under ambient laboratory conditions were used to evaluate changes in surface reflectance. Changes in organic functional group chemistry were evaluated using a 118 nm photoionization spectral map acquired by the μL²MS instrument at Johnson Space Center (JSC). Finally, the microstructure and composition of five focused ion beam (FIB) cross-sections (He*-irradiated matrix and olivine; H*-irradiated matrix, olivine, and pyroxene) were analyzed with a JEOL 2500SE 200 kV field-emission scanning TEM (STEM) equipped with an energy dispersive X-ray spectrometer (EDX).

Reflectance Spectroscopy Results: He*-irradiation causes spectral brightening (increase in albedo) and reddening (i.e., increasing reflectance with increasing wavelength) like that observed in [5]. Alternatively, H*-irradiation does not significantly change spectral slope or brightness. Both irradiated spectra show weakened ~1.0 μm (Fe²⁺ silicates), ~0.7 μm (Fe³⁺ silicates), and ~1.94 μm (water) absorption bands (Fig. 3b), with He* inducing more significant attenuation [6]. He*-irradiation also slightly strengthens absorptions at ~0.47 and 0.50 μm bands (Fe-oxides).

Surface Chemistry and Organics Results: XPS spectra demonstrate that He*- and H*-irradiation cause chemical changes at the surface of matrix and chondrule material. He*- and H*-irradiation greatly attenuate carbon peaks (C-C, C-H, and C-O bonds), suggesting that both ion types cause preferential removal of carbon-bearing species (or possibly their re-distribution in the sample by ion mixing or diffusion) within the upper-most 10 nm of the sample. High-resolution spectra of matrix material indicate that H*-irradiation alters sulfate minerals at the surface to sulfides via preferential sputtering of oxygen (Fig 1A). Similarly, H*-irradiation chemically reduces surface Fe³⁺ to native Fe²⁺ and a
small amount of Fe\(^0\) (Fig 1B).

Consistent with XPS results, µL-MS mapping at the 118 nm photoionization wavelength shows a ~30-40% reduction in overall organic abundance after irradiation. Concentrations of aromatic species remain relatively unchanged post-irradiation, suggesting aromatics may be more resistant to irradiation-driven chemical and structural modifications compared to other organic molecules.

**Figure 2.** Conventional TEM images of (A) He\(^+\)-irradiated matrix, (B) H\(^+\)-irradiated matrix, (C) He\(^+\)-irradiated olivine, and (D) H\(^+\)-irradiated olivine. Arrows indicate thicknesses of ion-affected regions.

**TEM Results:** TEM analysis of the He\(^+\)-irradiated matrix FIB-section shows a fairly continuous ion-affected vesiculated layer (> 100 nm) at the sample’s surface (Fig 2A). The vesicle density of this layer is very high, and individual vesicles can reach up to ~100 nm in size. High-resolution imagery indicates that amorphization reaches 125-175 nm below the surface. Ion damage differs in the H\(^+\)-irradiated matrix FIB-section. The vesiculated layer is uniformly <100 nm thick and the amorphization depth never exceeds 60 nm (Fig 2B).

The He\(^+\)-irradiated olivine FIB-section has an ion-affected region averaging 80-90 nm in thickness (Fig 2C). This region is dominated by amorphous olivine with some polycrystalline areas. In the H\(^+\)-irradiated olivine, the ion-affected layer is ~60 nm thick and dominated by polycrystalline olivine with few amorphous islands (Fig 2D). Both olivine samples possess similar vesicle densities and sizes.

Nano-particles are present in the vesiculated-amorphous layer of the H\(^+\)-irradiated pyroxene FIB-section (Fig 3). Approximately 3-5 nm in diameter, these nanoparticles have d-spacings consistent with an Fe-bearing phase (e.g., 0.15, 0.21, 0.22, and 0.24 nm), but the exact phase has not yet been determined. The He\(^+\)-irradiated olivine and H\(^+\)-irradiated pyroxene both possess a thin, dark, mottled, highly-strained boundary layer between the vesiculated-amorphous and crystalline regions, similar to that observed in Hayabusa particles [7,8].

**Figure 3.** High-resolution TEM image showing Fe-bearing nanoparticles (indicated by red circles) in the H\(^+\)-irradiated pyroxene FIB-section.

**Implications for Space Weathering on Primitive Bodies:** Ion irradiation of carbonaceous material yields complex results. XPS and µL-MS mapping show a net decrease of carbon associated with the alteration and removal of organics. XPS also shows a chemical reduction of iron and sulfides, which may indicate the production of Fe-bearing nanoparticles by ion irradiation (Fe-oxides, Fe-sulfides, metallic Fe). Trends in reflectance also suggest nanoparticle formation. Irradiation-induced attenuation of the 0.7 and 1.0 µm bands may reflect the breakdown of matrix phyllosilicates, partial reduction of iron, and/or minor production of nanophase particles [9]. The combination of absorption strengthening at 0.47 and 0.50 µm (Fe\(^{3+}\) oxides) and absorption weakening at 1.94 µm (OH/H\(_2\)O) may reflect the formation of Fe-oxide nanoparticles via dehydrogenation in reducing environments [e.g. 10]. Although the XPS and reflectance data can be explained by minor nanoparticle formation, nanoparticles are not universally identified in the TEM analysis. Nanoparticles were only confirmed in the H\(^+\)-irradiated pyroxene FIB-section. Decreased material density from vesiculation is likely increasing the penetration depth of ions in the samples. Additional chemical and microstructural TEM analysis is underway to further investigate this paucity of nanoparticles and constrain interpretations from coordinated results.