EFFECT OF SOLAR WIND SPACE WEATHERING ON PHOSPHORUS REDOX ON METAL-RICH ASTEROIDS. J. M. Christoph (correspondence: christophj@si.edu)¹, C. A. Dukes², and T. J. McCoy¹
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Introduction: A primary objective of the NASA Psyche Mission is to measure the oxidation-reduction (redox) state of a metal-rich asteroid, and thereby to assess the conditions of its formation [1]. Using its Gamma Ray and Neutron Spectrometer (GRNS) and Visible / Near-Infrared Imager, the Psyche spacecraft will quantify the surface abundance of some redox-indicating elements, possibly including Ni, Fe, C, Cr, P, and Si [1,2]. Active processes in the space environment chemically and physically modify asteroid surfaces, often causing them to appear different up close compared to Earth-based observations [3,4]. Space weathering by solar wind ion irradiation is a chemically reducing process that can preferentially remove one element over another from an exposed planetary surface, modifying the surface’s optical reflectance and spectral features [5-8].

We thus aim to quantify how the presence and chemical state of these redox-sensitive elements might change due to solar wind ion irradiation over geologic time. We focus on phosphorus in this presentation.

Experiment: We irradiated a thick section slab of the Landes iron meteorite (USNM 4847) with 1keV protons to simulate long-duration solar wind exposure. Landes is the most Ni-poor member of the IAB main group [9], and contains angular, millimeter-scale, nonmetallic inclusions similar to the Odessa type [10]. Within Landes’ inclusions are 10- to 100-micron-diameter grains of sulfide (troilite, daubréelite), carbide (graphite, cohenite), phosphide (schreibersite), phosphate (Cl-apatite), oxide (chromite), and silicate (olivine, pyroxene, plagioclase) minerals. Although Landes likely did not originate from asteroid Psyche [11], within its mineral assemblage are all the redox-sensitive elements the Psyche Mission expects to observe, which occur in both reduced and oxidized mineral phases [1].

Before irradiation, we mapped the thick section surface using backscattered-electron imaging and energy-dispersive X-ray spectroscopy (EDS) to locate each mineral phase of interest. We then quantified the abundances of major elements within each identified phase using electron microprobe (EPMA) point analyses, confirming previous measurements by [12].

The irradiation was carried out on a customized PHI Versaprobe III within the Laboratory for Astrophysics and Surface Physics at the University of Virginia. The Versaprobe integrates a keV floating-column ion gun for proton irradiation with an in-situ small-area X-ray Photoelectron Spectrometer (XPS), enabling simultaneous measurement of both the abundance and redox state of elements in the uppermost layers of atoms that are most readily disrupted by incident ions. One challenge of such a surface-sensitive characterization technique is atmospheric oxidation [8]; to minimize this, we mechanically abraded the sample surface with diamond under N₂ gas before placement in the sample introduction chamber. We then plasma-cleaned the surface with H₂ in an adjacent UHV chamber before transfer to the irradiation/analysis chamber. We obtained high-resolution XPS spectra from seven mineral phases before and irradiation, as well as survey XPS spectra at multiple fluence steps over the course of the irradiation. We aimed for a total fluence of 3×10^{18} H⁺/cm², at a flux of 10^{13} H⁺/cm²/s, to be consistent with previous experiments which simulated an exposure duration required to fully weather an exposed asteroid surface [8, 13].

Results & Interpretation: Our irradiation experiment on a multi-component natural sample provided a wealth of data; here we present preliminary results. High-resolution XPS spectra of the P-2p peaks in apatite [Ca₅(PO₄)₃Cl] and schreibersite [(Fe,Ni)₃P] are shown at the beginning and end of the irradiation (Fig. 1). Each photoelectron peak may be comprised of multiple sub-peaks, individually corresponding to different electron spin configurations in the 2p orbitals and varying electron bond polarization between nearest-neighbor atoms (chemical state).

![Fig. 1: P-2p peaks for apatite and schreibersite.](image-url)
In apatite, the overall intensity of the P-2p peak is significantly lower after irradiation, but the peak position does not change significantly, suggesting phosphorus in apatite is preferentially removed by sputtering but does not change redox state. The same effect is apparent in the Ca-2p peak (Fig. 2): before irradiation its only significant sub-peaks correspond to Ca-PO₃ bonds and an overlapping Mg Auger electron feature, while after irradiation a new Ca-O sub-peak pair appears. Thus, as phosphorus is removed from apatite by ion sputtering, calcium phosphate is transformed to calcium oxide.

![Graph showing before and after irradiation spectra](https://example.com/apatite-peak)

**Fig. 2: Apatite Ca-2p peak after irradiation, with fitted sub-peaks.**

In schreibersite, the intensity of the overall P-2p peak does not seem to change, however a change is apparent in the sub-peaks (Fig. 3). The most intense pair corresponds to Fe-P bonds in the 3/2 and 1/2 transitions and does not change significantly. Two more sets of sub-peaks are present before irradiation, corresponding to residual surface formation of PO₄³⁻ in atmosphere and Ni-P bonds. Both latter sub-peak pairs are significantly less intense after irradiation, indicating both removal of surface oxidation and breaking of Ni-P bonds, but not necessarily that phosphorus changes redox state in or is removed from the irradiated schreibersite.

**Implications for Psyche:** Phosphorus is a particularly useful redox indicator for Psyche due to its partitioning behavior during core formation. On an oxidized parent body, phosphorus tends to partition into the mantle as phosphate minerals, while on a reduced parent body it partitions into the core in metal and/or phosphide minerals [1]. Because phosphorus is both incompatible during core crystallization [14] and immiscible with sulfur-rich liquid [15], it concentrates in the final liquid to crystallize, as represented by the

![Graph showing before and after irradiation spectra](https://example.com/schreibersite-peak)

**Fig. 3: Schreibersite P-2p peak before irradiation, with fitted sub-peaks.**

IIAB and IIG iron meteorites [1]. We therefore might expect to measure abundant phosphorus associated with Ni-poor metal if Psyche’s parent body was highly reduced, or phosphorus associated with phosphate minerals overlying Ni-rich metal if it was oxidized.

Our observation of phosphorus removal from apatite, but not schreibersite, by H⁺ irradiation suggests that solar wind may decrease the abundance of phosphorus on an asteroid formed from an oxidized parent body, making its surface appear more reduced over time. We should thus take surface processes into account when interpreting Psyche’s redox state.

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