SPACE WEATHERING FEATURES IN A SULFIDE GRAIN FROM ASTEROID ITOKAWA L.C. Chaves[1], M.S. Thompson[1] S.N. Shuvo[1] [1]Purdue University, West Lafayette, IN, USA (lchavesm@purdue.edu).

Introduction: In 2010, the Hayabusa mission returned 1534 regolith particles from the S-type asteroid Itokawa to Earth [1]. S-type asteroids were long hypothesized to be the parent bodies of ordinary chondrites. Compared to ordinary chondrites, these asteroids exhibit spectral differences across the visible to near-infrared (VNIR) wavelengths including darkening (lower reflectance), reddening (increasing reflectance with increasing wavelength), and the attenuation of characteristic absorption bands. These spectral characteristics were thought to result from space weathering, a process which alters the chemical composition, microstructure, and optical properties of regolith on the surfaces of airless bodies. Petrological analyses of grains returned from Itokawa show a composition similar to LL4-6 chondrites, confirming the link between S-type asteroids and ordinary chondrites [1]. Historically, our understanding of space weathering processes has focused on silicate minerals which dominate lunar samples and the bulk of ordinary chondrites. However, sulfides have been identified in regolith grains returned from the S-type asteroid Itokawa [1] and are important accessory minerals in carbonaceous chondrites [2].

Previous transmission electron microscopy (TEM) analyses on Itokawa grains [3] have revealed the presence of amorphous rims that could result from vapor deposition caused by micrometeoroid impacts or redeposition of material sputtered by solar wind ions, and vesiculated textures that might have been produced by solar wind ion implantation. These microstructural and chemical features are similar to those which have been reported in space weathered lunar soils [4]. However, analysis of Itokawa particles revealed the presence of new, previously unreported space weathering features, chief among them Fe-sulfide nanoparticles (npFeS) [5]. The identification of npFeS particles is novel, as nanoparticles in space weathered lunar samples are mainly composed of Fe^0 [6]. The identification of S-bearing nanoparticles indicates that sulfide minerals may play an important role in the space weathering of more compositionally complex regoliths (e.g., on carbonaceous asteroids). It is important, therefore, to study the response of sulfides to space weathering, so here we report evidence of space weathering in a pyrrhotite grain from asteroid Itokawa.

Methodology: We analyzed the RB-CV-0121 particle allocated to us by the Japan Aerospace Exploration Agency (JAXA) that was previously identified to contain olivine, low-Ca pyroxene, and Fe sulfide. RB-CV-0121 has an angular shape and an approximate size of 26 µm in its longest dimension. It contains several sulfide phases (Fig. 1a) which are present both as inclusions and on the edges of the silicate-rich host grain. To maximize the number of thin sections retrieved from this sample, we adapted the hybrid ultramicrotomy/focused ion beam scanning electron microscopy (FIB-SEM) technique developed by [7]. The particle was embedded in epoxy and ultramicrotomed to obtain sections with approximate thickness of 50 nm, appropriate for analysis by transmission electron microscopy (TEM). After ultramicrotomy, thin sections were extracted from sulfide-rich areas using a FEI Helios NanoLab 660 FIB-SEM at University of Arizona. The transmission electron microscopy (TEM), scanning transmission electron microscopy (STEM), and energy-dispersive X-ray spectroscopy (EDX) analyses of the thin sections were performed using two TEMs at Purdue University: 1) a 200 keV FEI Tecnai T20 TEM equipped with an Oxford X-Max silicon drift EDX detector (SDD), and 2) a monochromated, aberration corrected 300 keV Thermo Fisher Themis Z FEG TEM, equipped with a Super X EDX detector.

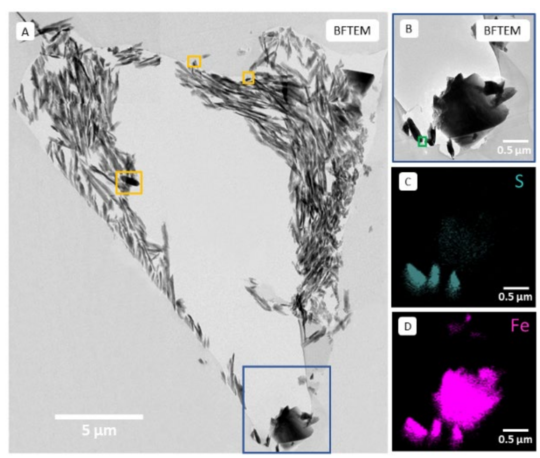

Fig. 1. Distribution of sulfide grains in RB-CV-0121. a) Bright field (BF)TEM image showing the location of sulfide grains in yellow and blue squares. b) Higher magnification BFTEM image of sulfide grains and their EDX maps showing c) S and d) Fe.

Results: Unique chemical and microstructural features were identified in the sulfide-bearing RB-CV-0121 regolith particle. Most of the sulfide grains are located near the edge of the particle and have sizes below 1 µm (Fig. 1b). Sulfides at the edges of the grain are targets of interest for analysis of space weathering features, as they are more likely to have experienced exposure to interplanetary space. High resolution TEM (HRTEM) images show lattice fringes with d-spacing values of 0.56 nm that correspond to (004) of monoclinic pyrrhotite (Fig. 2). HRTEM images show the presence of an outer rim on a sulfide grain with a uniform 5 nm thickness and without obvious lattice fringes. This rim is sulfur depleted compared to iron (Fig. 3a). The HRTEM and EDX analyses did not show the presence of nanoparticles. EDX data of other sulfides grains (detailed in Fig. 1a) do not show similar evidence of sulfur depletion.

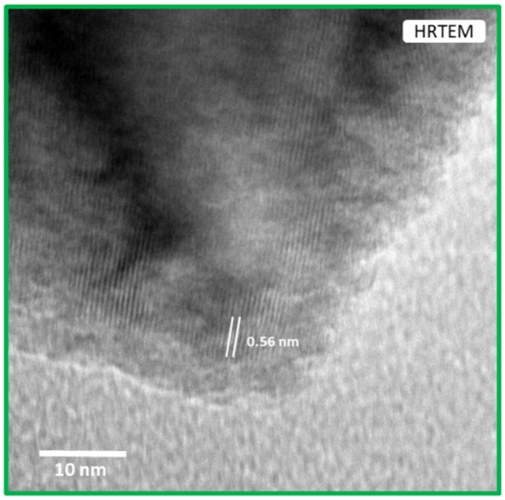

Fig 2. HRTEM image of a sulfide grain showing a rim with an approximate thickness of 5 nm. Lattice fringes give a d-spacing of 0.56 nm which matches pyrrhotite.

Discussion: Previous studies have identified sulfur depletion in disordered rims on pyrrhotite-bearing grains of asteroid Itokawa [8]. Additionally, TEM analyses have found metallic iron whisker-like structures on troilite surfaces as result of FeS decomposition produced by solar wind irradiation [9]. In this study, we identified sulfur depletion in the rim compared to its iron content. EDX data show that this rim is not enriched in any other element that may have resulted from of vaporization of the surrounding silicates (e.g., Si, Mg), indicating it did not likely form during a micrometeoroid impact event. The thickness of this rim is approximately 5 nm, similar to previous reports for pyrrhotite grains from Itokawa [8]. Furthermore, [8] identified the presence of solar flare tracks in olivine in contact with the sulfide, estimating a minimum exposure time (i.e. $3x10^4$ years), indicating this grain may have a similar exposure timescale. In addition, ion irradiation studies show the presence of sulfur depleted rims in troilite, similar to the chemical features seen here, after irradiation using 4 keV He^+ [10]. However, in situ Kr^{++} ion irradiation experiments on pyrrhotite did not show complete amorphization, but rather the breakdown only of the characteristic pyrrhotite superstructure [11]. Our results and their comparison to previous studies on Itokawa grains and ion irradiation experiments in sulfides suggest that this rim was formed through solar wind irradiation. We will run ion damage simulations in the stopping and range of ions in matter (SRIM) software to identify the physical parameters that might have produced the rim. These results will be compared to analyses of four other sulfide-bearing Itokawa particles allocated by JAXA.

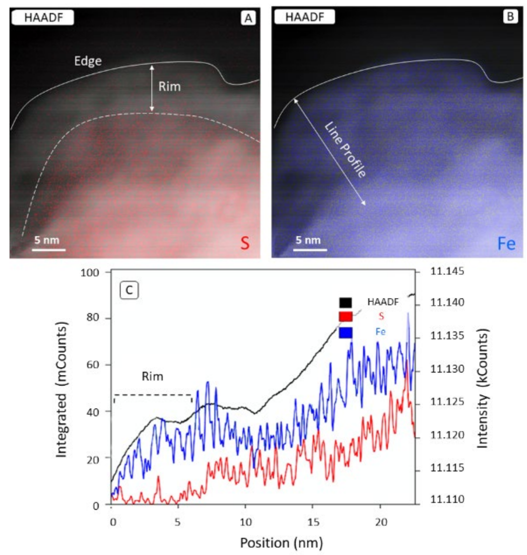

Fig 3. High angle annular dark field (HAADF) images, overlain with EDX maps of sulfide grain. a) S map showing depletion in rim compared to the b) Fe map. c) EDX linescan of the uppermost 25 nm of the grain showing the sample thickness and the variation of Fe and S along the profile.

References: [1] Nakamura T. et al. (2011) *Science*, 333, 1113-1115. [2] Bland P. A. et al. (2004) *Meteoritics & Planet. Sci*., 39, 3-16. [3] Thompson M. S. et al. (2014) *Earth, Planets and Space,* 66:89. [4]. Keller L. P. and McKay D. S. (1997) *Geochim.Cosmochim. Acta*. 61, 2331-2341. [5] Noguchi T. et al. (2011) S*cience*, 333, 1121-1124. [6] Thompson M. S. et al. (2016) *Meteoritics & Planet. Sci*., 51, 1082-1095. [7] Berger E. L. and Keller L. P. (2015) *Microscopy Today,* 23, 18-23. [8] Keller L. P. and Berger E. L. (2014) *Earth, Planets and Space,* 66:71 [9] Matsumoto T. et al. (2020) *Nature Comm,* 11:1117. [10] Keller L. P. et al. (2010) LPSC *XLI* Abstract #1172. [11] Christoffersen R. and Keller L. P. (2011) *Meteoritics & Plaet. Sci*., 46, 7, 950-969.