

A TYPE IIA CHONDRULE FRAGMENT FROM COMET 81P/WILD2 IN STARDUST TRACK C2052,2,74

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Introduction: Fragments of Comet 81P/Wild2 collected by the Stardust Mission have varied origins from wide-ranging heliocentric distances [1-4]. More than half of the material in an Fe K-edge XANES (X-ray absorption near edge fine structure) survey of eleven Stardust tracks was found to have formed in the inner solar system [5].

We have done coordinated analyses of a 23 μm by 9 μm fragment from Stardust track C2052,2,74, named Iris, using a combination of in-aerogel synchrotron x-ray measurements including XRF maps and XANES, followed by extraction and ultramicrotomy for coordinated Scanning Transmission X-ray Microscopy (STXM) and TEM analyses.

Sample: Stardust Track C2052,2,74 is a 6-mm long track containing three terminal particles and numerous fragments in the bulb. We extracted Track 74 from its aerogel tile in three keystones (Fig. 1a).

In-aerogel characterization: Track 74 was characterized using the microprobe beamline 10.3.2 at the Advanced Light Source (ALS). We used μXRF to make major element maps of the entire track from all 3 keystone fragments and selected 56 particles with sufficient Fe Kα emission for micro-XANES spectroscopy [5]. For the whole of Track 74, the Fe K-edge XANES fit to 56% of total Fe present as Fe²⁺, 6% as Fe metal, 38% as sulfide. The dominant fit was olivine (Fo₆₀ to Fo₈₀).

Fig. 1c shows a three-color Fe-Cr-Ni fine map (0.5 μm pixels and ~1.5 μm beam) of Iris. Fe K-edge XANES of the whole particle (broad beam) fit 58% of total Fe to olivine, 12% Fe as sulfide and the remaining 30% Fe as other Fe²⁺. The map shows three distinct Cr hotspots, 2-5 μm in diameter. Bulk Iris Cr/Fe was calculated from XRF spectra taken at 9710 eV, corrected for background, for the efficiency of the CCD detector, and for the difference in K-shell fluorescence yield. The measured value Cr/Fe = 0.047 is 4.5 X CI.

μXRD mapping at several energies (between 7 keV and 14 keV) acquired at ALS beamline 10.3.2 combined with energy scans at μXRD ALS beamline 12.3.2 showed Iris comprises at least 10 different phases and confirmed the presence of olivine.

Iris was extracted from its keystone (Track 74c) in a smaller volume of aerogel using a technique similar

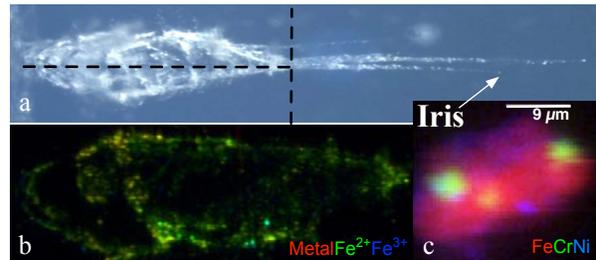


Figure 1. a) Track 74 was extracted as 3 keystones divided along the dashed black lines. b) Iron oxidation state map of one of the bulb halves shows the bulk of the iron to be Fe²⁺, with some Fe metal near the track entrance. c) Fe-Cr-Ni XRF map of Iris shows 3 Cr hotspots.

to keystoning[6]. An ultralene “surgical tent” secured the ~4 mm keystone, allowing a ~100 μm wide aerogel wafer containing Iris to be removed, without damaging the other two terminal particles. Iris and the surrounding aerogel was embedded in epoxy Embed 812 for ultramicrotomy. The particle was oriented, using the X-ray maps as guides, with olivine at the bottom and one Cr hotspot at the top. In order to conserve as much of the particle as possible for subsequent analysis, 100 nm slices were taken only until we had confirmed sections of Iris on TEM grids (copper, 200 mesh with a 200 Å α-C-film).

Ultramicrotomed section characterization: Section 9 was analyzed at ALS Beamline 11.0.2 Scanning Transmission X-ray Microscope (STXM). The beamline uses Fresnel zone plates to focus an ellipsoidal polarizing undulator X-ray source to a ~25 nm beam spot over the energy range 200 to 2000 eV. Most elements accessible in this range using K-edge or L-edge XANES spectroscopy, with 0.1 eV energy resolution. We used STXM to make element maps and multispectral XANES images. First, we checked for cometary carbon, correcting for the epoxy and α-C-film backgrounds. We then mapped Ca, Cr, Fe, Mg, Mn, N, Na, Ni, O, Si, Ti and V using the difference between peak and pre-edge absorption. We collected multispectral XANES in small regions for Mg and Na K-edges, Fe and Cr L₂₃-edges. Na-XANES does not suffer from Na volatilization as does EDX which makes STXM quantitation of Na-rich plagioclase phases more accurate. Sections 9 and 4 were subse-

quently analyzed in a CM200 TEM with a Gatan energy filter at National Center for Electron Microscopy using STEM/EDX/EELS, EFTEM, and HRTEM for high resolution element quantification and mineralogical imaging. Section 3 was analyzed at University of Washington by STEM/EDX for quantification and imaging. Mineral identifications were verified by electron diffraction.

Iris mineralogy: The major phases identified in Iris Section 3 are olivine (Fo₆₆ to Fo₆₈), oligoclase (An₁₇ to An₂₀), Al-rich glass and iron sulfide. In Section 9, the section furthest into the grain, olivine (Fo₆₈) was also the major component. We identified one oligoclase grain (Ab₇₁An₂₁ from STXM Na-XANES and Ca, Al, maps). The oligoclase also contained Mg such that Al/Mg \cong 2000. We found a 2x1 μ m chromium-rich spinel with formula (Mg_{3.9}Fe_{4.7})(Cr_{7.2}Al_{8.2})O₃₂ and minor components (relative to O₃₂) Ti_{0.16} V_{0.08} and Mn_{~0.1} (STEM/EDX quantification). A monoclinic low-calcium pyroxene (En₅₃ Fs₄₇ Wo_{<1}) was attached to Ca-Al-rich glass. Multiple <100 nm-sized iron sulfide grains in Section 4 confirmed the Fe K-edge XANES fits for sulfide.

The three Cr hotspots in Fig 1c are likely to be similar chromium-rich spinel grains. Their grain sizes are 3 to 5 μ m, which are consistent with grain sizes of chromite observed in Type II chondrules [7].

Vanadium content of the chromite was measured via STEM/EDX after correcting for Ti K- β interference. The formula 100V/(Cr+Al) has been related to oxygen fugacity, log(fO₂) relative to the Iron- Wüstite buffer (IW) by Papike et al. [8]. For the Iris chromite, 100V/(Cr+Al) = 0.56 to 0.65 from which we obtain log(fO₂) = IW \sim +3.

Discussion: The presence of chromite is indicative of recrystallization from a melt and grain sizes are similar to those seen in Type II chondrules. The major component of Iris is FeO-rich olivine (Fo₆₆). The presence of monoclinic low-calcium pyroxene is evidence for a fast cooling rate [9]. The oxygen fugacity derived from V content and the FeO-enriched olivine suggests Iris was formed in a more oxidizing environment than previous Mg-rich chondrule-like Wild 2 materials reported [4]. The high oxygen fugacity could also be due to internal buffering by FeO [10]. The retention of sodium in Na-rich plagioclase is also consistent with flash heating and a high cooling-rate in a high fO₂ environment [10]. The Ca-Al glass resembles chondrule mesostasis. We conclude that the texture and mineralogy of Iris are consistent with Type IIA chondrules.

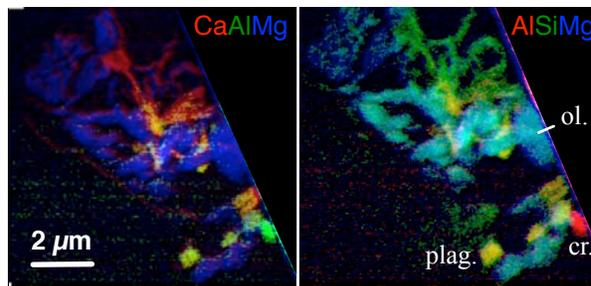


Figure 2. STXM element maps of Iris,9. Absorption difference maps, pixel size 100 nm. a) Ca-Al-Mg-. Yellow regions are Ca-Al rich, Purple regions are Ca-bearing Mg-Fe silicates. b) Al-Si-Mg map, the minerals are labeled as for Fig. 3.

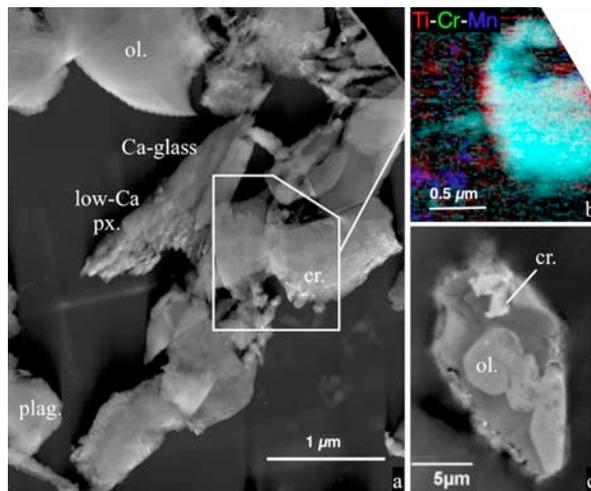


Figure 3. Iris (a) Section 9 STEM/BSE image showing ol. = olivine (Fo₆₈); plag. = oligoclase; low-Ca px. = monoclinic pyroxene (<1% Ca); cr. = chromite spinel also shown in (b) STXM absorption maps of Ti-Cr-Mn for the chromite grain. c) SEM/BSE image of the potted butt.

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