AQUEOUS ALTERATION IN THE KUIPER BELT: EVIDENCE FROM HYDRATED INTERPLANETARY DUST PARTICLES.

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Introduction: Edgeworth-Kuiper belt objects (EKBOs) formed in the outer reaches of the protoplanetary disk and thus avoided much of the high temperature processing experienced by bodies in the inner solar system. For this reason, they contain a wealth of information on the nature of nebular solids and the chemical conditions in the earliest solar system. Astronomical observations of EKBOs have been limited largely to the surface chemistry of the ices covering these small and difficult to observe bodies [1]. The mineralogy of EKBO objects are poorly known, but clues regarding their mineralogical makeup come from studies of samples from short period comets (e.g. Wild2), and interplanetary dust particles (IDPs) produced by collisions in the Kuiper belt [1].

Interplanetary dust particles from objects in the solar system (mainly comets and asteroids) spiral in towards the Sun under the influence of Poynting-Robertson (PR) drag forces and accumulate solar flare energetic particle tracks. Recent work has shown that the observed solar flare track densities ($\sim 10^{10}$-10^{11}/cm^2) in these IDPs are ~two orders of magnitude higher than expected if they were derived from main belt asteroids or Jupiter family comets and thus require an origin from outer solar system source bodies such as EKBOs [2]. The track-rich IDPs include representatives from the two major groups of IDPs: the chondritic-porous, anhydrous IDPs and the chondritic-smooth, hydrated IDPs, although rare IDPs with mineralogies intermediate between these two groups are known [3]. Here, we report on the mineralogy, composition, organic matter content, and isotopic charcteristics of track-rich hydrated IDPs, and implications for aqueous alteration in outer solar system bodies.

Materials and Methods. The 10-20 µm sized IDPs are embedded in elemental sulfur and partly sectioned using ultramicrotomy to produce thin sections ~50 nm thick for transmission electron microscopy measurements as well as NanoSIMS measurements of H, N, and O isotopes. The remainder of the IDP is extracted from the sulfur and pressed into Au for quantitative electron microprobe elemental analysis (including C). Following the EPMA measurements, the IDPs are analyzed by secondary ion mass spectrometry at UCLA for their oxygen isotopic compositions.

Mineralogy. The hydrated IDPs in this study are low porosity objects dominated by fine-grained Mg-rich phyllosilicates (saponite and lesser serpentine) with finely dispersed Fe,Ni-sulfide grains (pyrrhotite and pentlandite). Mg-Fe carbonates or their thermal decomposition products are common. Framboidal magnetite occurs in two of the IDPs. Anhydrous silicates such as forsterite, enstatite, diopside, and quartz are minor, but important constituents, as they are the grains that record solar flare tracks. The preservation of solar flare tracks and minerals with low decompositions temperatures suggest that these IDPs were not strongly heated during atmospheric entry, consistent with low atmospheric entry velocities.

Insights into the nature of the phyllosilicate precursors come from studies of the partly altered anhydrous IDPs (termed “hybrid IDPs by [3]). The hybrid IDPs contain both anhydrous and hydrated material, where the anhydrous material consists of Mg-rich olivines and pyroxene, and amorphous silicates (glass with embedded metal and sulfides – GEMS) grains, and the hydrated portions are dominated by saponitic phyllosilicates. Saponite is the predicted alteration product of GEMS grains based on the Mg/Si and Fe/Si compositions of GEMS grains [4]. The Nakamura-Messenger study [3] demonstrated that GEMS grains are highly reactive at low temperatures and are easily altered to phyllosilicates.

Organic Matter. The bulk chemical compositions of hydrated IDPs are within a factor of 2 of CI abundances except for C, which is enriched, on average, by a factor of 4 or greater over CI values [5,6]. The hydrated IDPs contain abundant carbonaceous material finely dispersed throughout matrix and as discrete nanoglobules (individuals and clusters as noted previously [7-9]) that commonly show D- and ^{15}N enrichments. The nanoglobule H and N isotopic compositions are consistent with an outer solar system or presolar origin [7]. The nanoglobules typically contain minor S that is probably present as aromatic S, and in one hydrated IDP shows enhanced C=O functionality in globule rims [9]. Infrared spectra from microtome thin sections show strong aliphatic C-H stretches consistent with the presence of short-chain aliphatic hydrocarbons in these IDPs.

Isotopic Compositions. To date, we have obtained oxygen isotope analyses of four C-rich hydrated IDPs that reveal a range of Δ^{17}O values, from +1.8 ‰ to +37.4 ‰ [6]. The oxygen isotopic compositions of the hydrated IDPs are distinct from known carbonaceous chondrite groups and show evidence for interaction with a ^{16}O-poor reservoir .

Results and Discussion. The unusual oxygen isotopic compositions, high carbon contents, and the abundance of isotopically anomalous nanoglobules suggest that these carbon-rich hydrated IDPs are derived from primitive chondritic sources that are distinct from known chondritic meteorites. The extent of aqueous alteration and the mineralogy of hydrated IDPs are most similar to CI chondrites, although their isotopic compositions and carbon abundances are distinct [6]. The observed solar flare track densities place the origin of these hydrated IDPs from sources beyond the orbits of the gas giant planets, most likely the Edgeworth-Kuiper belt, the major source of dust beyond 10 AU [10]. Hydrated minerals are reported on two Kuiper belt objects based on visble spectra showing a weak 0.7 µm absorption attributed to an Fe^{2+}-Fe^{3+} charge transfer transition from oxidized iron in phyllosilicates [11].

There are multiple potential sources of liquid water in EKBOs. The larger objects, if they accreted early, may have contained sufficient radiogenic elements to mobilze (melt) interior volatiles [12], although the Al-Mg isotopic systematics from Comet Wild2 samples suggest late accretion of that Kuiper belt object after the decay of ^{26}Al [e.g. 13]. Alternatively, aqueous fluids could have been produced during low velocity collisional processes among EKBOs that produced transient heating sufficient to melt water ice. These short-lived fluids could potentially result in heterogeneous hydration of anhydrous silicates at 10 micrometer scale observed in the “hybrid” IDPs.

The abundance of EKBO dust in the Earth’s stratosphere is difficult to constrain, and further systematic studies will be required to evaluate their contribution to the stratospheric dust population. Our initial estimate, based on the IDPs we have analyzed to date, is that up to a 1/2 of the hydrated IDPs collected in the stratosphere are derived from EKBOs. Most of the dust produced by EKBOS is ejected from the solar system, but ~20% of the dust reaches the inner solar system [10], with highly circularized, low eccentricity orbits and low Earth encounter velocities [14].

Conclusions: IDPs with solar flare track densities $>10^{10}/cm^2$ are derived from dust-producing objects in the outer solar system, most likely Edgeworth-Kuiper belt objects because the observed track densities are far too high for the IDPs to be derived from the main asteroid belt or Jupiter family comets via PR drag. The majority of track-rich IDPs are anhydrous, with a mineralogy typical of “cometary” IDPs, but a subset of track-rich hydrated IDPs record parent body aqueous alteration effects through interactions with ^{16}O-poor H_2O on a EKBO parent bodies. The aqueous alteration activity likely resulted from the ehat generated by collisional processes among EKBOs.

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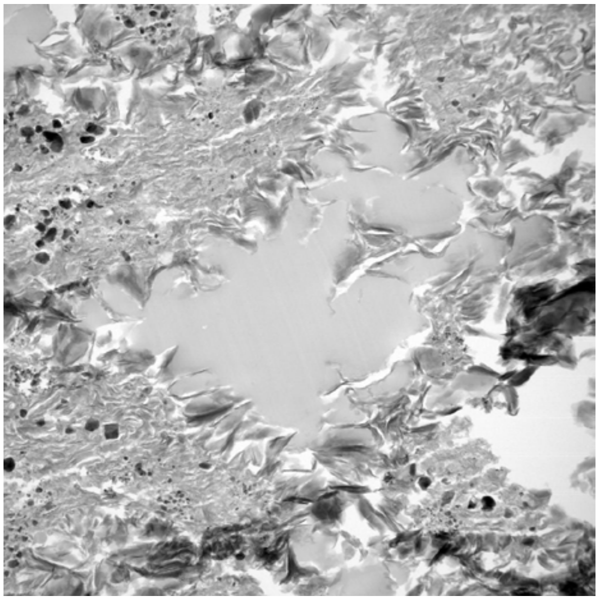

Figure 1. Bright-field STEM image of L2098B1 showing coarse-grained phyllosilicates and a large aggregate of carbon nanoglobule material. The field of view is 10 µm. The sub-µm dark grains are FeNi sulfides.

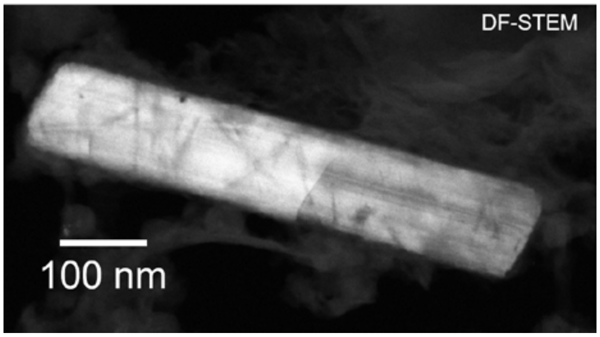

Figure 2. Darkfield STEM image of solar flare tracks in an enstatite platelet from U2153M1. The track density is ~5x10^{10} cm^{-2}.