Surprisingly High Abundance of Na and Cr-rich Calcic Pyroxenes in Stardust Tracks.

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Introduction. The return of samples by the Stardust (SD) spacecraft from comet Wild 2 in January, 2006 has provided an unprecedented opportunity to study materials from the outer Solar System. The initial phase of mineralogical studies demonstrated that a large range of minerals – olivines, pyroxenes, sulfides, metal grains and many accessory phases – were present in the 52 aerogel tracks in which samples were studied [l]. We have continued mineralogical studies of 15 SD tracks and have noted a remarkably high abundance of Na+Cr-rich silicate phases. Of the 15 tracks that we have studied, seven contain high Ca pyroxenes including diopsides, augites and pigeonites with high or unusually high Na and Cr contents. An eighth track contains a sodic and chromium-rich amphibole, richterite [2]. Most of the SD high Ca pyroxenes have compositions that are unlike those observed in chondrules or matrix in most chondritic meteorites in that the SD grains contain significantly higher Na and Cr and sometimes higher Mn.

Here, we report compositional data and other mineralogical features of these Na+Cr-rich calcic pyroxenes that were observed in the seven SD tracks. We compare these grains with the closest analogues from chondritic meteorites – Na and Cr-rich augites and diopsides from chondrules in type 3.0 ordinary chondrites (OC) and R chondrites – and show that most of the SD grains contain significantly higher Na_2O and Cr_2O_3. At least one SD calcic pyroxene is also rich in MnO. Though we do not yet uniquely understand the origin and nature of these grains or whether they may have a common origin to the meteoritic analogue pyroxenes in OC and R chondrites, we believe that such a high proportion of unexpected sodic and chromium-rich high Ca pyroxene is significant to the origin of comet Wild 2.

Techniques. The SD grains were prepared by keystoning individual tracks from aerogel blocks [3], followed by flattening between glass slides and embedding with acrylic resin. Individual grains were cut from each flattened track and microtomed into < 100 nm thick slices and placed onto either Cu or Au grids containing 10 nm thick carbon thin-films. The microtomed slices were examined with a 200 kV Tecnai F20 FEG TEM/STEM using standard techniques including bright- and dark- field imaging, electron diffraction, high resolution imaging and EDX compositional analysis. The EDX analyses were performed with a light element EDAX X-ray detector using either embedded Tecnai analysis software (written by the former Emispec Corporation) or a stand-alone running-in-parallel EDAX EDX system with Genesis software. The spectra were fit using multiple least square fitting routines and k-factors were measured with in-house mineral standards or the NIST thin-film standard SRM2063a.

Results. Ferrosilite (Fe/Fe+Mg) contents, pyroxene type, and Na_2O, Cr_2O_3 and MnO wt% from 20 individual microtomed mineral shards from 7 tracks are listed in Table 1. Three separate fragments were studied in Track 77. The table shows that most pyroxenes observed were augites followed by diopside and pigeonite. Fe contents span a large range and vary from Fs 3.2 – 24.2. Fs content is generally much narrower within individual fragments; this may simply be a result of analyzing shards of single larger mineral grains that were broken and scattered during microtoming.

Table 1: Na-Cr rich high Ca pyroxenes from SD tracks.

Track No.	Frag Name	Phase	Fs	Na_2O wt%	Cr_2O_3 wt%	MnO wt%
7	Arinna	augite	5.3	2.4	3.01	0.26
17	ValHrt	augite	24.2	0.6	0.7	0.35
17	ValHrt	augite	20.0	1.1	1.5	0.34
27	Sitara	augite	6.8	4.7	9.8	0.34
27	Sitara	augite	9.1	5.7	10.4	0.00
27	Sitara	augite	9.2	5.7	13.4	0.32
41	Isis	augite	22.8	1.9	3.8	0.33
41	Isis	augite	21.9	1.2	2.9	0.33
41	Isis	augite	23.9	1.0	2.1	0.32
57	Febo	diop	4.2	1.7	1.3	0.00
58	Noni	augite	12.9	3.8	3.0	0.29
77	Puki	augite	20.2	1.23	1.4	0.32
77	Puki-B	diop	14.0	2.1	1.4	0.32
77	Puki-B	diop	17.6	2.5	2.9	0.00
77	Puki-B	diop	17.5	1.7	1.4	0.32
77	Puki-B	diop	16.9	2.4	2.5	0.00
77	Puki-C	pigeon	3.5	0.5	2.6	8.4
77	Puki-C	pigeon	3.2	1.0	2.9	8.0
77	Puki-C	pigeon	5.7	0.4	1.8	10.0
77	Puki-C	augite	8.1	0.7	1.7	12.3

Key: Diop=diopside, pigeon=pigeonite, frag=fragment, Fs=ferrosilite.

Values for Na_2O vary from 0.4 – 5.7 wt% while Cr_2O_3 ranges between 0.7 – 13.4 wt%. Na_2O vs Cr_2O_3 is plotted in Figure 1 along with reference fields of high Ca pyroxenes (augites and diopsides) from chondrules from type 3.0 OCs and the R chondrite Rumuruti [4]; these fields are visible in the lower left-hand corner of the figure at lower Na_2O and Cr_2O_3. Pyroxenes from the two chondrite fields contain some of the highest measured Na and Cr contents in high Ca pyroxene from chondrules and therefore represent the closest meteoritic analogues to the SD pyroxenes. The plot shows that the SD pyroxenes are as much as 5X higher in Na_2O and 4X higher in C_r2O_3 than the meteoritic pyroxenes.

SD pyroxene MnO contents range from 0.0 (trace) to 0.35 wt% with the exception of a single augite fragment from track 77 (Puki-C) which contains MnO up to 12.3 wt%. These MnO values compare to type 3.0 OC and Rumuruti augites/diopsides of 0.1 – 2.5 wt% and 0.1 – 0.38 wt%, respectively. The chondrule pyroxene values are similar (R) or higher (OC) than the SD pyroxenes except for Puki-C pyroxene which contains significantly higher MnO.

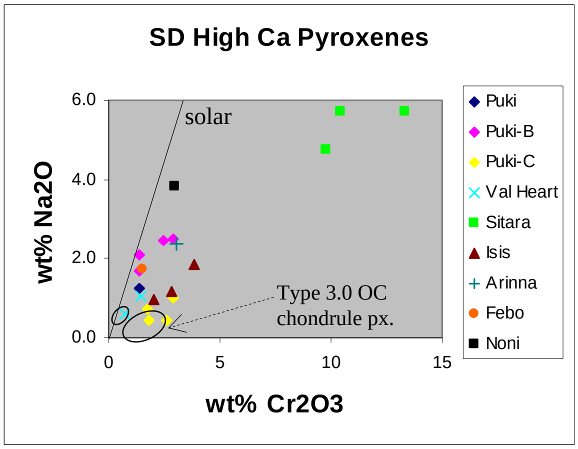

Fig 1. Wt% Na2O vs Cr2O3 for high Ca pyroxenes from 7 Stardust tracks. Small unmarked oval field is from Rumuruti high Ca pyroxenes in chondrules. Px = pyroxene.

To gain a better understanding of the nature of these grains it is vital to know which phases they occur with. Unfortunately, context information is difficult to determine in SD tracks due to the fragmentation of particles during capture and is further compounded by shattering of grains during microtoming. However, we have noted that in at least 4 fragments (from 3 tracks), Na+Cr rich calcic pyroxenes occur with Fe-rich olivines (Fa_{28-42}) and occasionally direct contacts between these grains can be observed. Figure 2 shows a SD Na-Cr rich augite from the fragment Isis in contact with Fo_{69}. Similar contacts occur in fragment Puki-B suggesting a co-genetic relationship may exist between these Na+Cr calcic pyroxenes and the Fe-rich olivines.

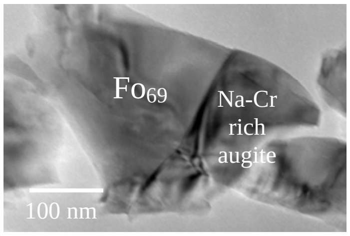

Fig. 2. Grain boundary contact between Na+Cr-rich augite and Fo_{69} in SD track 41 (Isis).

Discussion. Several important questions arise from this study. Why do so many tracks (~ 50%) contain calcic pyroxenes enriched in Na and Cr (and sometimes Mn) and could there have been a common source for these grains that contributed material to comet Wild 2? What is the origin of these grains and are they linked to high Ca pyroxenes from OC or R chondrites which also have elevated Na and Cr (though much lower than the SD pyroxenes)?

Several interpretations for the origin(s) of these grains seem plausible. Na and Mn are moderately volatile elements while Cr is a borderline MVE and thus, it is possible that a nebular heating event may have evaporatively removed these elements from pre-existing phases which were then condensed onto and reacted with more refractory pre-existing high Ca pyroxenes causing the observed enrichments of these elements. The SD pyroxene Na/Cr ratios < solar Na/Cr (see Figure 1) imply that if true, this would require a fractionated gas. A second possible scenario suggests that an oxidized and fractionated gas (or gases) rich in Na and Cr, and perhaps Mn, variably reacted with pre-existing Fe-bearing high Ca pyroxenes. In this scenario, Mn would have to be depleted from the nebular gas as the SD pyroxenes are not as widely enriched in Mn (compared to OC and R chondrites) as Cr and Na. Perhaps Mn was removed from the gas by a prior condensing phase such as forsterite. LIME forsterites have been observed in some IDPs and UOCs which were interpreted as condensates [5]. A third interpretation suggests that some of the high Ca pyroxenes could have formed directly from melts, chondrule-like or even planetary; evidence for this is present in at least two fragments where Na+Cr-rich calcic pyroxenes are in direct contact with Fe-rich olivine (Figure 2). Measured Na, Cr and Mn wt% from this co-existing augite/olivine pair are shown in Table 2.

Table 2: Na, Cr and Mn el wt% in coexisting pyroxene and olivine in SD fragment Isis (see Figure 2).

	Na	Cr	Mn	Fe/Fe+Mg
Augite	0.8	1.9	0.3	0.22
Fo_{69}	trace	trace	0.48	0.31

The table shows that Na and Cr are present in higher abundances in the augite than the olivine while Mn is present in higher abundance in olivine. Experimental and measured distribution coefficients for basaltic/andesitic systems predict this partitioning behavior between these phases [6,7] during equilibrium crystallization and thus the distribution of these elements is consistent with these minerals crystallizing co-genetically from a ferromagnesian melt.

Conclusions. Seven SD tracks (from 15 observed) contain high Ca pyroxenes rich in Na and Cr compared to OC and R chondrite chondrule pyroxenes (which are the most analogous meteoritic pyroxenes to the SD grains due to their elevated Na_2O and Cr_2O_3 contents compared to other chondrites). A unique interpretation for the origin of these grains is not possible yet and scenarios envisioning condensation or evaporation in fractionated nebular gas or crystallization from liquid melts or recrystallization as a result of metamorphic heating are all plausible.

References: [1] Zolensky et. al. (2006), *Science*, Vol 315, 1735-1739, [2] Joswiak et al. (2007), LPSC XXXVIII, [3] Westphal et al. (2004), *MAPS*, Vol 39, no. 8, 1375-1386, [4] Brearley and Jones (1998), *Planetary Materials*, Vol 36, 3.1–3.398, [5] Klock et al. (1989) *Nature*, Vol 339, 126-128, [6] Duke, J. M. (1976), *J. Petrology*, Vol 17, 499-521, [7] Henderson, P. (1982), *Inorganic Chemistry*, Pergamon Press, 353pp.