Origin of low-Ca pyroxenes in comet samples: Evidence for igneous formation in the nebula like chondrules.

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Introduction: Studies of solid particles from comet Wild 2 and a giant cluster IDP, which is likely to have originated from a comet [1,2], show links to chondritic meteorites indicating that comets and asteroids likely accreted some materials from common source regions [1-9]. Comets formed in the cold, relatively placid outer Solar System (SS) and are believed to have largely remained unchanged since their formation [3]. In contrast, asteroids, which formed and evolved in the inner SS were variously modified by internal and external processes including aqueous alteration, thermal metamorphism and impact brecciation. Because comets and asteroids have different evolutionary histories and regions of formation, yet share some common materials, an important question arises as to whether processes that modified asteroids may have also affected comet materials. Insight into this question can help resolve the relative timing between accretion of common materials, provide information where comet grains may have originated and show whether some comets experienced active internal processes.

Here we use minor elements – Al, Cr and Mn – in low-Ca pyroxenes (Lpx) in comet Wild 2 grains and from a giant cluster IDP to provide insight into their origins. Our study provides evidence that the Lpx minerals likely formed by igneous processes in a solar nebula environment like chondrules. The data imply that the comet grains were not incorporated into parent bodies (PB) that experienced any significant thermal metamorphism prior to their accretion into comet Wild 2 or the giant cluster IDP PB. In addition, O isotopes obtained from a recent study [2] on some of the comet Lpx grains suggest derivation from diverse nebular sources, including both ordinary (OC) and carbonaceous chondrite (CC) regions that fed asteroids.

Sample Analyses: Fifty one low-Ca pyroxenes from 13 Stardust tracks and 33 Lpx grains from the giant cluster IDP were analyzed by TEM/EDX for major and minor elements. The Wild 2 samples, encased as terminal particles or in bulb walls in aerogel, were flattened between glass slides and embedded with acrylic resin. The giant cluster IDP, a large particle that was collected in the stratosphere, consists of thousands of grains, submicron to ~40 µm in size, and has chemical and physical properties consistent with an origin from a comet [1,2]. Particles from the IDP were individually hand-picked and washed in hexane to remove adhering Si oil and embedded in acrylic or epoxy resin. All samples were cut to thicknesses <70 nm and placed on 10 nm-thick C films on Cu or Au TEM grids and studied with a Tecnai TF20 STEM located at the University of Washington by conventional TEM/EDX techniques. Typical errors are <5% for major elements and ~30% for minor elements.

Results: Approximately ½ of the Lpx grains from comet Wild 2 and ~1/3 of those from the giant cluster IDP were observed as single mineral grains. The others were present in polycrystalline assemblages most often with olivine, augite and/or sulfides. In both Wild 2 and the giant cluster IDP, Lpx Mg#'s range from 79-100 and 71-99, respectively.

A 2D kernel density estimate (KDE) plot of Al_2O_3 vs Cr_2O_3 from 202 Lpx grains from chondrites [10-16] is shown in Fig. 1 along with 75 discrete Lpx analyses from comet Wild 2 (triangles) and the giant cluster IDP (squares). The magenta, green and yellow regions show distributions for Lpx minerals from chondrules from type 3 chondrites, including ordinary, CR and CV groups and Acfer 094 while the Lpx distribution from thermally metamorphosed type 4-6 chondrites is shown in blue.

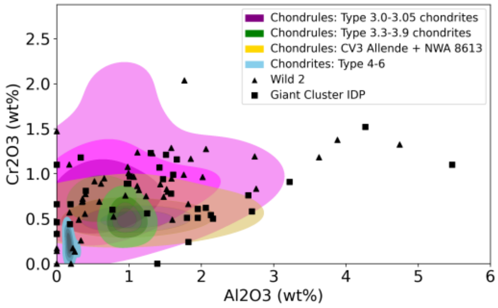

Fig. 1. KDE plot of Al_2O_3 and Cr_2O_3 in Lpx minerals in chondrules from type 3 chondrites, Lpx from type 4-6 chondrites, comet Wild 2 and a giant cluster IDP.

Lpx analyses from comet Wild 2 and the giant cluster IDP have elevated Al_2O_3 and Cr_2O_3 abundances similar to chondrules from type 3 chondrites. Six comet Lpx analyses with low Cr and Al contents are most similar to type 4-6 chondrites (blue shaded region). These latter grains all have Mg#'s > 99 and may have condensate origins (e.g. [7,9]).

Histograms displaying the MnO abundances of Lpx minerals from comet Wild 2, the giant cluster IDP, and type 3 and type 4-6 chondrites are shown in Fig. 2 [10-16]. The histograms illustrate that Lpx's from the comet samples have variable MnO contents and are most similar to chondrules from type 3 chondrites and are unlike Lpx's from type 4-6 chondrites which show convergence of MnO.

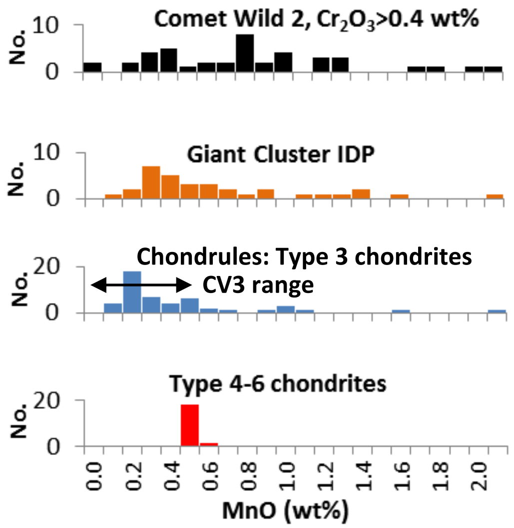

Fig. 2: Histograms of MnO (wt%) abundances in Lpx from comet Wild 2, the giant cluster IDP, chondrules from type 3 chondrites and Lpx in type 4-6 chondrites.

Discussion. Similar to Cr in olivine [17], minor elements in low-Ca pyroxenes are useful indicators of degree of thermal metamorphism, and can be used to identify petrologic type. This is evident in Fig. 1 where Lpx minerals from chondrules in a range of type 3.0-3.05 chondrite groups (OC, CR, ungrouped Acfer 094, magenta) and CV3 chondrites (yellow) display elevated Cr and Al concentrations which were likely inherited from their liquid melts during crystallization in the nebula. Chondrules from higher type 3 subtypes (3.3-3.9, green) also show elevated Al and Cr concentrations but reflect partial loss of Cr and perhaps Al. This is in contrast to Lpx grains from type 4-6 chondrites (blue) which have lost most of their Cr and Al. This pattern in Lpx minerals suggests that as thermal metamorphism progressed on their PBs, Cr was lost by diffusion, probably to chromite, followed by Al from formation of feldspar, a common mineral in type 4-6 chondrites. Thus, Al and Cr abundances in Lpx grains, like Cr in olivine, can be used to determine whether Lpx grains experienced significant thermal metamorphism from a parent body process (type 4-6) or were formed by igneous processes in the nebula, akin to chondrules, and remained largely unaltered.

Elevated Al and Cr concentrations in most Lpx grains from comet Wild 2 and the giant cluster IDP (Fig. 1) demonstrate that Lpx minerals in comets are most similar to chondrules from type 3 chondrites and therefore suggest formation in a nebular environment like chondrules rather than from PBs where thermal metamorphism was active. Similarly, MnO in Lpx grains from the comet samples is most comparable to chondrule Lpx's from type 3 chondrites and do not show convergence like those in type 4-6 (Fig. 2). The comet Lpx grains with low Al and Cr which plot with type 4-6 chondrites (Fig. 1) all have low Al, Cr, Mn, Mg#'s>99 and occur as monomineralic grains suggesting they may have condensate origins.

Oxygen isotopes from 6 comet Wild 2 [7] and 11 Lpx grains [2] are shown in Fig. 3. The Lpx grains plot in a variety of locations w.r.t. the terrestrial fractionation, PCM and CCAM lines suggesting derivation from both OC and CC regions [2]. The two Wild 2 ^{16}O-rich Lpx grains (Fig. 3, inset) are presumed condensates [7]. Both have low Al, Cr and Mn concentrations, Mg#'s>99 and occur as monomineralic grains.

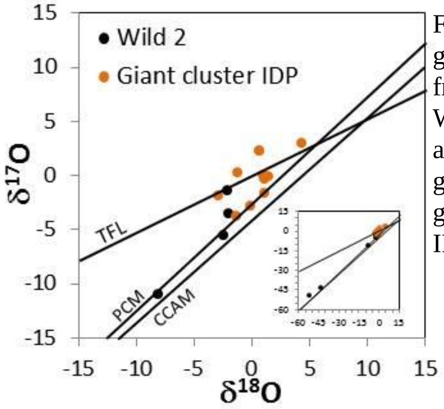

Fig. 3: Oxygen isotopes from 6 comet Wild 2 [7] and 11 Lpx grains from a giant cluster IDP [2].

Conclusions: Elevated minor element abundances, including Cr, Al and Mn in Lpx from comet Wild 2 and a giant cluster IDP of probable cometary origin indicate that the comet grains formed in an igneous nebular environment like chondrules and are not fragments of thermally altered PB materials. O isotopes further show that the comet grains originated in multiple source regions including OC and CC reservoirs.

References: [1] Joswiak et al. (2017) *MAPS* 52:1612-1648. [2] Zhang et al. submitted *EPSL*. [3] Brownlee (2004), in Met. Comets, Planets, *Treat on Geochem*. [4] Nakamura et al. (2008) *Science* 321: 1664-1666. [5] McKeegan et al. (2006) *Science* 314: 1724-1727. [6] Nakashima et al. (2012), *EPSL*, 355-365. [7] Defouilloy et al. (2017) *EPSL*, 465: 245-154. [8] Frank et al. (2014) *GCA* 142: 240-259. [9] Fukuda et al. (2020) *GCA* 293: 544-574. [10] Berlin et al. (2011) *MAPS* 46: 513-533. [11] Ushikubo et al. (2012) *GCA* 90: 242-264. [12] McCoy et al. (1991) *GCA* 55:601-619. [13] Kessel et al. (2007) *GCA* 71: 1855-1881. [14] Slater-Reynolds et al. (2005) *MAPS* 40: 745-754. [15] Hertwig et al. (2019) *MAPS* 54: 2666-2685. [16] Rudraswami et al. (2011) *GCA* 75: 7596-7611. [17] Grossman and Brearley (2005) *MAPS* 40: 87-122.