CRYSTALLINE SILICATES IN COMETS: MODELING IRREGULARLY-SHAPED FORSTERITE CRYSTALS AND ITS IMPLICATIONS ON CONDENSATION CONDITIONS

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Introduction: Crystalline silicates in comets are a product of the condensation in the hot inner regions (T $\gtrsim 1400$ K [1]) of our proto-planetary disk or annealing at somewhat lower temperatures (T $\gtrsim 1000 - 1200$ K) [2, 3, 4] in shocks coupled with disk evolutionary processes that include radial transport of crystals from their formation locations out to the cold outer regions where comet nuclei formed.

The grain shape of forsterite (crystals) could be indicative of their formation pathways at high temperatures through vapor-solid condensation or at lower temperatures through vapor-liquid-solid formation and growth [5, 6, 7]. Experiments demonstrate that crystals that formed from a rapidly cooled highly supersaturated silicate vapor are characterized by bulky, platy, columnar/needle and droplet shapes for values of temperature and supersaturation, T and σ, of 1000–1450°C and < 97, 700–1000°C and 97–161, 580–820°C and 131–230, and <500°C and > 230, respectively [7]. The experimental columnar/needle shapes, which form by vapor-liquid-solid at lower temperatures (<820°C), are extended stacks of plates, where the extension is not correlated with an axial direction: columnar/needles may be extended in the c-axis or a-axis direction, can change directions, and/or are off-kilter or a bit askew extending in a combination of the a- and c-axis direction.

DDSCAT Computations of $Q_{\rm abs}$: Figure 1 shows the IR absorption efficiencies for the four DDSCAT shapes. From the descriptions and SEM images in [7], we associate the highest temperature condensate bulky shape with bricks with forsterite dimension (b-axis is the longest dimension) and platy shapes with platelets where the b-axis is the shortest dimension. A simple DDSCAT rendition of the experimentally derived columnar/needle shape is a rectangular prism (or column) with two axes equal and the third axis (either a- or c-axis) elongated matching the columnar/needle growth pattern cited by [7].

Based on Fig. 1, clear distinctions in spectral signatures are expected for crystals that condense from supersaturated vapors at different temperatures. For example, extensions in the a- and/or c- axis (represented in Fig. 1 with the 14 x 7 x 18 Rectangular Plate, a-Column, and c-Column) produce a 10.5 μm peak that does not exist for grain shapes with a dominant b-axis (represented in Fig. 1 with the Forsterite Dimension Brick). Extension of the c-axis also significantly increases the strength of the 23 μm feature as is shown in Fig. 1 with the c-Column. The 10.5 μm peak signifies platy and columnar/needle shapes, implying a lower condensation temperature and higher supersaturation. A significantly enhanced 23 μm feature (relative to other features) signifies c-axis columnar shapes, implying condensation temperatures lower than 820°C and supersaturation higher than $\sigma > 131$.

Implications: Comet spectral energy distributions [8, 9] commonly show a 11.2 μm peak without a strong and distinguishable 10.5 μm companion peak [10], and for those comets with high enough signal-to-noise to distinguish the peaks in the 15–30 μm wavelength range do not have a significantly enhanced 23 μm feature relative to other features [2, 11, 12, 13]. A brief examination of external protoplanetary disk spectra shows these same trends where the 23 μm peak is not overwhelmingly dominant [8, 9]. If the 10.5 μm peak is not strong, then the grain shape is not platy nor a-columnar and if the 23 μm feature is not overwhelmingly dominant then the grain shape is not c-columnar. This implies the grain shape revealed by observations is bulky. While this type of analysis cannot for certain determine the formation history of the crystalline grains, it provides a strong suggestion that the environmental conditions under which the crystals formed favored condensation at temperatures greater than 1000°C (1273 K). Condensation origin for forsterite crystals is strongly supported by laboratory examination of forsterite crystals in cometary IDPs [6, 14], which are described as having equant and tabular crystal habit, and in Stardust samples [15, 16, 17]. Hence, our library of grain shapes can be used in an effort to ascertain the formation conditions of forsterite crystals that are observed in an astronomical sources.

References: [1] H.-P. Gail (2010) in *Lecture Notes in Physics, Berlin Springer Verlag* (Edited by T. Henning) vol. 815 of *Lecture Notes in Physics, Berlin Springer Verlag* 61–141 doi. [2] D. E. Harker, et al. (2002) 580:579 doi. [3] D. H. Wooden, et al. (2005) in *Chondrites and the Protoplanetary Disk* (Edited by A. N. Krot, E. R. D. Scott, & B. Reipurth) vol. 341 of *Astronomical Society of the Pacific Conference Series* 774–+. [4] D. Wooden, et al. (2007) *Protostars and Planets V* 815–833. [5] A. Tsuchiyama (1998) *Mineralogical Journal* 20(2):59. [6] J. P. Bradley, et al. (1983) 301:473 doi. [7] H. Kobatake, et al. (2008) 198:208 doi. [8] J. Olofsson, et al. (2009) 507:327 doi. arXiv:0908.4153. [9] I. Oliveira, et al. (2011) 734:51 doi.arXiv:1104.3574. [10] D. H. Wooden, et al. (1999) 517:1034 doi. [11] D. E. Harker, et al. (2004) 615:1081

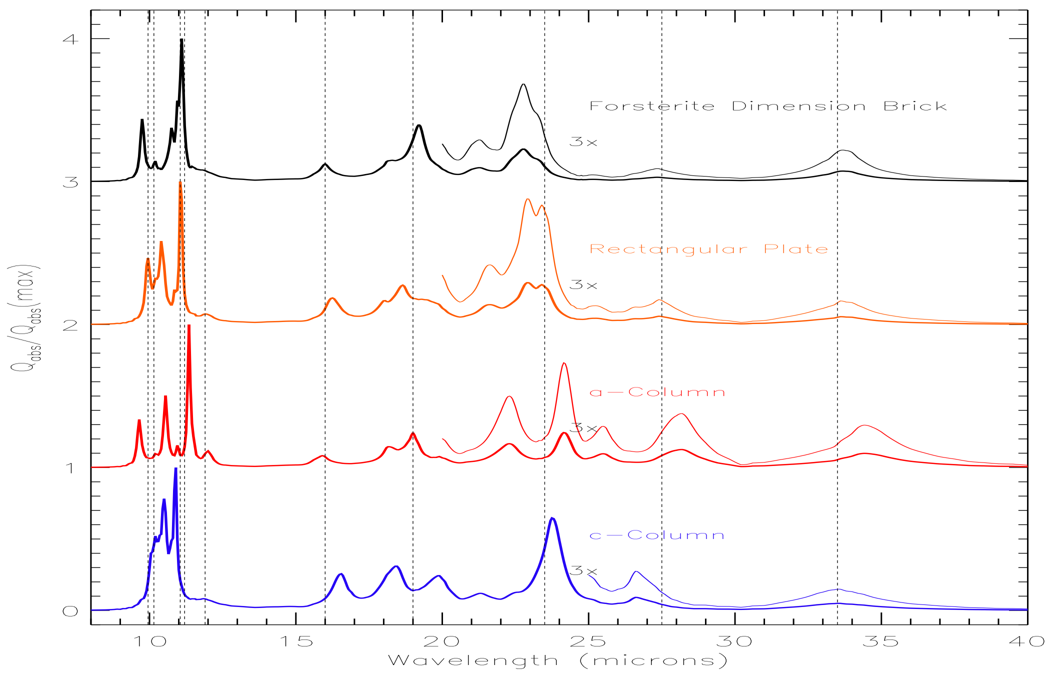

Figure 1: DDSCAT calculated Q_{qabs} for a_{eff} = 0.1 μm analogs to the bulky, platy, and comlumnar/needle forsterite condensates presented in [7]. From top-to-bottom, bulky = forsterite dimension brick (*black*), platy = rectangular plate (*orange*, and columnar/needle = a-Column (*red*) and c-Column (*blue*). The number of dipoles, i.e. lengths, along the optical a-,b-, and c- axes are 14 x 7 x 18, 60 x 15 x 15, and 15 x 15 x 60 for the rectangular plate, a-Column, and c-Column, respectively. The far-IR Q_{abs} values have been multiplied by 3 to increase feature contrast.

doi. [12] C. M. Lisse, et al. (2006) *Science* 313:635 doi. [13] W. T. Reach, et al. (2010) 208:276 doi. arXiv:1001.4161. [14] F. J. Molster, et al. (2003) in *Lunar and Planetary Institute Science Conference Abstracts* (Edited by S. Mackwell & E. Stansbery) vol. 34 of *Lunar and Planetary Institute Science Conference Abstracts* 1148–+. [15] D. Brownlee, et al. (2006) *Science* 314:1711 doi. [16] T. Nakamura, et al. (2008) *Meteoritics and Planetary Science* 43:247 doi. [17] A. Tsuchiyama, et al. (2009) *Meteoritics and Planetary Science* 44:1203 doi.