THE ORIGIN OF CRYSTALLINE SILICATES IN COMETS AND LARGE SCALE MIXING IN THE SOLAR NEBULA D. E. Brownlee[1], D. Joswiak[1], J. Bradley[2] and G. Matrajt[1]
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Introduction: The return of comet samples by the Stardust mission provides a new opportunity to better understand the origin of crystalline materials around stars and to provide direct information on large scale mixing in the solar nebula. There is a considerable body of astronomical data and interpretations on the nature and origin of cometary and circumstellar silicates and there also is a complimentary body of meteoritic information on solid materials that existed in the inner parts of the solar nebula. The comet samples that accreted beyond Neptune provide new sample-derived insight into these issues and provide a means to assimilate the sometimes disparate inferences made by the meteoritic and astronomical communities.

The nature of cometary and circumstellar silicates: Infrared spectra indicate generally close similarity between crystalline dust released by solar system comets and dust observed around other stars. The first astronomical evidence for the presence of crystalline silicates in comets came from the detection of fine structure on the 10 micron infrared "silicate feature" of comet Halley [1,2]. A sharp feature near 11.2µm was first observed during the comet's 1986 apparition and this was attributed to the presence of crystalline olivine. This was a surprising discovery because the general expectation was that cometary silicates would be amorphous. The smooth profile of the observed silicate feature of interstellar dust has widely been interpreted as evidence that on the order of 99% or more of interstellar silicates are amorphous [3,4]. Infrared spectra taken in the 3 to 40µm region for comet Hale-Bopp, Tempel 1 (after the ejection of material from the Deep Impact mission) and from circumstellar dust show a rich number of features some of which have been attributed to crystalline silicates including forsterite and enstatite. The spectra indicate similar compositions from the different sources but the makeup of the grains has been interpreted differently. Hale-Bopp was interpreted as a mix of Fo, En, silica, carbon, iron, iron sulfide and two amorphous silicates by Min et al. [5]. As is traditionally done in the astronomical community, the amorphous component was estimated to be a mix of "amorphous olivine and pyroxene". It was estimated that only 7.5% of the dust from Hale-Bopp was crystalline. With a generally similar spectrum, Temple 1 was modeled by Lisse et al. 2006 [6] to be a mix dominated by ferrosilite and forsterite with lesser amounts of amorphous olivine, niningerite (Mg,Fe)S, smectite, diopside, orthoenstatite and carbonates. The implied crystallinity of Temple 1 is very high although spectra of the natural outflow before the spacecraft impact were essentially featureless. This "mineralogical change" is likely to be misleading and just an artifact of impact related processes that breakup cometary materials into the submicron grains that produce infrared silicate spectral features.

Origin: The presence of crystalline materials in comets and in circumstellar regions is commonly attributed to thermal annealing of interstellar materials, heating them to temperatures near 1000K [7]. Because the majority of circumstellar real estate is cold, the required heating effects are usually attributed to transient effects such as shocks [8]. In the case of the solar system this transient heating may occur near the giant planets and then the grains are transported outward by turbulent diffusion [9]. Because of the difficulty of forming forsterite from any amorphous precursors, it has also been suggested that this phase might be a condensate from higher temperature regions [8,9].

Stardust Samples: The initial results from Stardust shed important new insight into these problems and indicate that many cometary silicates are products of much more severe environments that those needed to cause annealing. Crystalline materials dominate Wild 2 grains larger than a micron that are found in the bottom halves of aerogel capture tracks. They are also often rather coarse-grained. Forsterite and enstatite are probably the most common silicates in comet Wild 2 but, for reasons described below, it seems highly unlikely that they formed by annealing of interstellar grains particularly those with olivine or pyroxene elemental compositions. They formed by processes that occurred at much higher temperatures.

The Fo and En grains are often one or two orders of magnitude larger than interstellar grains, the few that have been isotopically analyzed are not anomalous and they contain a wide ranging distribution of minor elements such as Al, Ca, Cr and Mn that cover the same distribution pattern seen for Mg rich olivines from primitive chondrites. In addition to forsterite, the comet contains a range of moderately Fe rich olivines clearly showing that the comet is unequilibrated. The minor element compositions of the forsterites show a wide range of compostions including refractory forsterites with Ca >0.7wt %, LIME forsterites with high Mn and grains with high Cr. The analyses are usually done in the TEM on 70nm thick microtome sections and errors due to interference from nearby grains can usually be shown not to be a significant problem. The wide range of minor element abundances seems to be inconsistent with an origin by annealing of amorphous pre-solar grains that were also of submicron size. It not obious what process could amorphous phases to have some of the rather exotic minor element compositions that are observed. Although the number of grains that have been analyzed is still limited, the range of minor element abundances in the cometary olivine is generally consistent with olvine grains in primitive meteorites as complied by Simon and Grossman [12]. The similarity of the rather odd dispersion of minor element contents as a function of iron content, for primitive chondrites and Wild 2, is a strong argument that the Wild 2 olivines and those in primitive chondrites have similar origins. Meteoritic olivines are usually considered to have origins related to some combination of igneous, alteraton or condensation processes. In constrast to astronomical predictions, they are usually not considered to be products of annealing of amorphous IS grains. The refractory forsterites (RF) appear to be similar among different types of primitive chondrites and Pack et al. [13] have suggested that they came from a common reservoir. Because similar RFs are also found in Wild 2, this common source may have distributed material across the entire solar system and not just the asteroid belt where chondrite parent-bodies formed. They suggested that RFs formed from refractory-rich melts, possibly liquid condensates.

“Amorphous Minerals”: The collected comet samples do contain amorphous material but there is no evidence that amorphous silicates with olivine or pyroxene stoichiometric compositions exist except possibly as very minor components. The lack of such precursor materials as well as minor element and isotopic compositions suggest that olivine and pyroxene seen in comet Wild 2 did not form by annealing. Furthermore, the lack of clear evidence for the precursors or the annealing process suggests that stoichiometric amorphous silicate with olivine or pyroxene composition was not an important material in the solar system and that annealing did not produce the the phases seen in either comets or chondrites. While these “amorphous minerals” may be useful as components to model astronomical infrared spectra it is likely that they are not important components of dust around stars.

Many of the Wild 2 particles that are larger than a few microns are small “rocks” composed of multiple phases. As described elsewhere [14,15] some of these rocks can be linked to highly processed nebular materials such as CAI’s, chondrules and possible Ameboid Olivine Aggregates. One of the major findings of the early analysis of Stardust samples has been the discovery that highly processed nebular materials that are found in chondrites are also found in a Kuiper belt comet. This implys that on the order of 10% of the comet is composed of inner solar nebula material, formed by high temperatures processes, that was transported to edge of the solar nebula. Although the nebula may not have been well mixed there was mixing of materials on the largest spatial scales. The inner solar system materials that sprinkled on the Kuiper Belt must have also been sprinkled on all solar system bodies. By analogy to the solar system, a similar origin may commonly occur for minerals observed around other stars.

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