

THE ORIGIN OF THE CRYSTALLINE SILICATES IN OUR SOLAR SYSTEM. F. J. Molster¹, J. P. Bradley² and M. L. Sitko³, ¹ESTEC/ESA, RSSD-ST, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, frank.molster@esa.int, ²School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, USA, john.bradley@mse.gatech.edu, ³Department of Physics, University of Cincinnati, Cincinnati, OH 45221-0011, USA, sitko@physics.uc.edu.

Introduction: The apparent discovery of presolar silicates within a chondritic interplanetary dust particle (IDP) [1] places renewed emphasis on the origin of silicate minerals within the solar system, particularly those silicates within cometary interplanetary dust particles. Although crystalline silicates are ubiquitous in primitive meteoritic materials, most of them appear to have formed within the solar system. The formation of crystalline silicates requires high temperatures and the discovery of crystalline silicates around evolved stars provides new insight on their formation mechanisms. Some crystalline silicates in the solar system (like SiC in meteorites) may have been transported from evolved stars via the interstellar medium (ISM). However, crystalline silicates are not detected in the ISM, suggesting that direct transportation of large quantities of crystalline silicates from evolved stars is unlikely. Therefore most crystalline silicates must have formed inside the early Solar System. Here we address the question of the origin and history of the crystalline silicates in the Solar System using the information other astronomical observations have provided us.

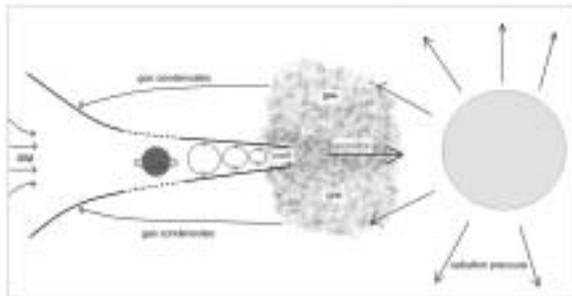


Figure 1: Schematic overview of the formation and transportation of crystalline silicates around the young Sun.

Crystalline Silicates in the Galaxy: Crystalline silicates are found in several environments in the Galaxy and their presence or absence in these environments is an important indicator of their formation and destruction mechanisms. A short overview follows:

Evolved Stars. Since the launch of the infrared space observatory (ISO) [2] it is clear that crystalline silicates are formed around evolved stars [3]. These crystalline silicates are Fe-poor enstatite and forsterite [4]. The

ISO data even suggests that the crystals may be essentially Fe-free like some of the grains found in IDPs.

Interstellar Medium. Infrared spectra of the ISM show no evidence of crystalline silicates. Based on these spectra the maximum percentage of forsterite that can be present is less than 1% of the total amount of silicates. For enstatite, which has intrinsically weaker features this value could be a little higher, but also no identification has been made yet. It has been suggested by several authors that the crystalline silicates are simply hidden in the interstellar medium [e.g. 5]. However, an effective method to hide these silicates has not been advanced. Even very small crystalline silicates particles (~10nm diameter) are detectable in the matrix of an amorphous silicate structure (Fig. 2). It is expected that the crystalline silicates are destroyed in the ISM primarily by supernova shock waves [6].

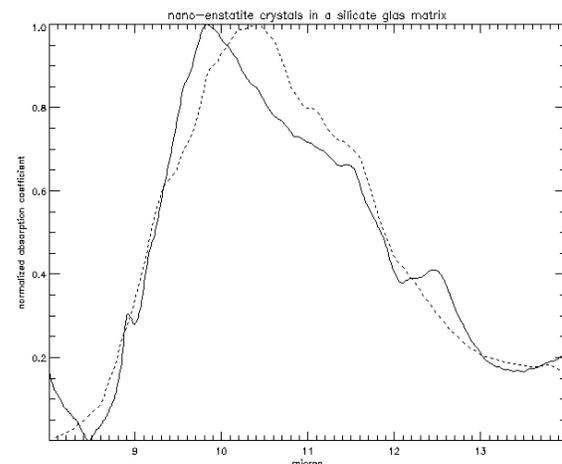


Figure 2: The normalized mass absorption coefficient (MAC) of amorphous smokes with ~5% of enstatite nano-crystals (solid line) compared to a calculated (MAC) of amorphous silicates and 5% of enstatite crystals of an arbitrary size (dashed line).

Young Stars. Most young stars only show hot (>200K) crystalline silicates. At the longer wavelengths hardly anything is seen of the crystalline silicates [7]. This implies that the main fraction of crystalline silicates is present at the hot inner edge of the accretion disk and not throughout the disk.

Solar System. For the purposes of this discussion we subdivide Solar System crystalline silicates into 3

groups. I) Large ($>1 \mu\text{m}$ diameter) Fe-rich crystalline silicates ($\geq 10 \text{ mol } \% \text{ FeO}$), II) Fe-free ($\leq 2 \text{ mol } \% \text{ FeO}$) that are typically $< 1 \mu\text{m}$ in size and sometimes exhibit compositional and/or crystallographic evidence of vapor phase growth, and III) “relict” crystalline forsterite or enstatite grains, that are heavily radiation damaged and found inside GEMS (Fig. 3). The first type of crystalline silicates are typical of dust that accreted within the vicinity of the asteroid belt, while the other two types are found as a dust component in (less processed) IDPs that are expected to come from comets originating outside the orbit of Jupiter.

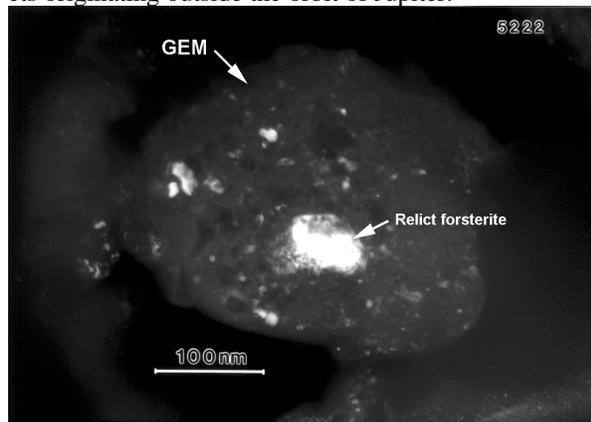


Figure 3: Relict forsterite grain inside a GEM.

Formation of Crystalline Silicates: Around evolved stars crystalline silicates are likely formed via gas-phase condensation. Experiments of Rietmeijer et al. [8] show that the formation through gas phase condensation will result in separate Mg and Fe silicates and no mixed Fe-Mg-silicate. This agrees with the pure Mg-rich crystalline silicates (enstatite and forsterite) found in the ISO observations. Up to now no evidence has been found for Fe-rich crystalline silicates. Equilibrium calculations show that Fe should preferentially condense as metal [9].

Another method to produce crystalline silicates is by the crystallization of amorphous silicates, either due to annealing or by crystallization via a melt. Both processes require a high temperature, so this process is only expected to play a role in the accretion disks of young stars, especially at the inner-edge, where the required temperatures are easily reached. The presence of hot crystalline silicates in the dust spectra of young stars points to this type of crystalline silicate formation. Since it is unlikely that condensed amorphous silicates would have the same stoichiometric composition as crystals, annealing would likely produce multiple minerals. An examination of the $10 \mu\text{m}$ region of several young stars does show evidence for other materials like quartz [10], although quartz is rare in primitive meteoritic materials.

Formation of Crystalline Silicates in the Solar System: From astronomical observations it is possible to propose a plausible scenario that describes the formation of crystalline silicates in the Solar System (Fig. 1).

Fe-containing crystalline silicates are likely formed by the crystallization of (molten) amorphous (Fe-containing) silicates due to the high temperatures close to the sun. Since in a disk the highest temperature is expected to be in the center plane, where also the largest particles resides, it immediately explains the large size of these particles, with respect to the other crystalline silicates. Turbulence inside the disk has transported these materials to larger distances. However, the formation of a giant planet like Jupiter has probably prevented further migration outwards.

Some Fe-poor crystalline silicates show evidence of growth via gas-phase condensation [11] very close to the central star. The properties seem to be very similar to that of the crystalline silicates formed in the outflows of evolved stars. A size sensitive transportation mechanism may have transported the small particles to distances beyond Jupiter by transporting them not through but over the disk (see Fig. 1). The size distribution of these particles is consistent with radiation pressure as transportation mechanism; still the X-wind scenario [12] can also not be excluded at the moment.

Heavily irradiation damaged ‘relict’ forsterite (and enstatite) grains may be survivors of the ISM. (Fig. 3). It is possible that a (large) part of the GEMS structure is in fact a heavily irradiated and damaged presolar forsterite (or enstatite) particle of which bits and pieces survived. The total abundance of the relict crystalline silicate grains in IDPs appears to be well below the present day detection limits for such grains in the ISM. New observations of Messenger et al. [1] show that there are abundant presolar silicate grains in a cluster IDP. The mineralogical identification of these grains is clearly of utmost importance.

References: [1] Messenger S. et al. (2002) this conference. [2] Kessler M.F. et al. (1996), A&A 315, L27-L31. [3] Waters L.B.F.M. et al. (1996), A&A 315, L361-L364. [4] Molster F.J. et al. (2002) A&A in press. [5] Wooden D.H. et al. (2000), Icarus 143, 126-137. [6] Demyk K. et al. (2001) 368, L38-L41. [7] Meeus G. et al. (2001), A&A 365, 476-490. [8] Rietmeijer F.J.M. et al. (1999), APJ 527, 395-404. [9] Gail H.-P. & Sedlmeyer E. (1999) A&A 347, 594-616. [10] Bouwman J. et al. (2001), A&A 375, 950-962. [11] Bradley J.P. & Brownlee D.E. (1983), Nature 301, 473. [12] Shu F.H. et al. (1996), Science 271, 1545-1552.