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# Crystallization of Silicate Particles By Shock Waves

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**Abstract.** Crystalline silicate dust particles have been found in some comets, though progenitors of those dust particles are thought to be amorphous. Here, the origin of the crystalline particles was investigated based on the shock-wave heating mechanism. We find that appropriate shock waves can crystallize amorphous dust particles and conditions of these shock waves (shock velocity and pre-shock gas density) are clarified.

The gas density in the solar nebula and the shock velocity that may be induced in comet forming regions by some mechanisms were discussed. It was suggested that comets formed in a region closer than about 20 AU to the Sun can contain the crystalline particles, whereas comets formed in a further region can hardly have them.

## 1. Introduction

Crystalline silicate dust particles have been found in some long period comets (Hanner *et al.* 1994). However, progenitors of those particles are thought to be amorphous. Thus, amorphous silicates are expected to be crystallized by some mechanism in the solar nebula or in comets, though the mechanism is not clearly understood.

Harker and Desch (2002) proposed that the shock-wave heating mechanism may be responsible for the crystallization of dust particles in comets. However, they showed the possibility of the mechanism for only a limited number of cases. It is still not clear to what extent the mechanism can be applied or if there are limitations to the mechanism.

Here, we propose that shock-wave heating can crystallize amorphous dust particles in comet forming regions. If there are appropriate shock waves, dust particles are heated and crystallized. Shock-wave heating has been investigated as a mechanism that formed chondrules in meteorites (e.g., Hood & Horanyi 1991; Iida *et al.* 2001). It seems that shock wave heating works not only in meteorite-forming regions, but also in comet-forming regions.

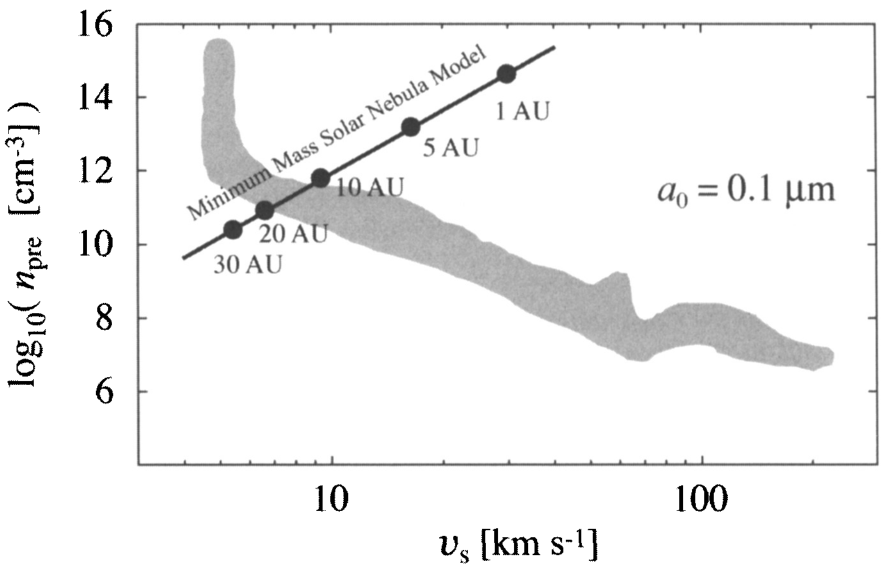


Figure 1. Conditions of shock waves for silicate crystallization.

## 2. Shock-Wave Heating Model

Basic mechanism of the shock wave heating is as follows. Let us suppose a shock wave passes a gas medium containing dust particles with a dynamical equilibrium, i.e., they do not have a relative velocity. Then the gas is accelerated and obtains some amount of velocity, while dust particles tend to remain in the initial position. The relative velocity between dust particles and gas causes drag heating. If the intensity of heating is high enough, dust particles can be crystallized.

We have developed the numerical model that simulates 1-dimensional plane-parallel steady shock flow including dust particles. In this model, the dynamics of the gas flow and the dust particles are treated in detail. Details of the model are described in Iida et al. (2001) and Miura & Nakamoto (2005).

Crystallization of dust particles is evaluated by the silicate evolution index (SEI) provided by Hallenbeck, Nuth, & Nelson (2000). This index was derived by a series of experiments of annealing. We calculate the SEI along the thermal history of the dust particle and evaluate if the particle is crystallized or not.

## 3. Silicate Crystallizing Shock Waves

We have carried out numerous calculations with various shock velocities and pre-shock gas densities and examined if those shock waves can crystallize the dust particles or not. Results for the initial particle radius $a_0 = 0.1\mu m$ are summarized in Figure 1. Gray colored region represents shock wave conditions with which dust particles are crystallized properly.

## 4. Origin of Crystalline Dust in Comets

In order to clarify the origin of crystalline particles in comets, we should specify the nature of shock waves that might have crystallized dust particles in comet forming region. However, it is not easy to estimate the gas density and the flow velocity in the comet forming region in the solar nebula. One possible shock generation mechanism is the accretion flow from the parent molecular cloud core that generates shock waves at the surface of the disk. In this case, the velocity of the shock is expected to be of the order of $\sqrt{2}\,V_{\rm K}$, where $V_{\rm K}$ is the Kepler velocity of the disk. Since the shock velocity is high enough, the dust particles can be crystallized by those shock waves, if the gas density is adequate. On the other hand, some shock waves might be generated in the disk by some other mechanisms, such as the density waves induced by the gravitational instability (Wood 1984; Harker & Desch 2002), eccentric motion of planetesimals (Hood 1998), or another unknown mechanism. If this is the case, the shock velocity should be of the order of or less than $V_{\rm K}$. Here we assume that the solar nebula is represented by the minimum mass solar nebula model (Hayashi, Nakazawa, & Nakagawa 1985) and draw a line in Fig. 1 which shows the relation between the mid-plane gas density and the Kepler velocity. Then, we can see from Fig. 1 that the shock waves generated in a region $R \lesssim 20$ AU can crystallize dust particles, whereas shock waves in $R \gtrsim 20$ AU cannot. This suggests that comets that formed in the inner region of the disk ($R \lesssim 20$ AU), can be recognized as long period comets containing crystalline dust particles, while comets formed in the outer region of the disk ($R \gtrsim 20$ AU), such as the Jupiter-family comets, should not have crystalline dust particles if radial mixing due to diffusion does not take place in the disk.

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