# HETEROGENEOUS GRAIN DESTRUCTION NEAR THE SUN

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**Abstract.** Catastrophic fracture of heterogeneous grains consisting of refractory matrix and trapped icy inclusions is examined. As such a grain approaches the Sun after release from the comet, the saturation pressure of icy inclusions increases, and finally exceeds the crack-extension-force necessary for onset of unstable fast fracturing. Subsequently a growth of cracks results in a facture of the grain.

The calculation revealed that obsidian and magnetite grain, respectively, of radius 100 $\mu$m with 10% water-ice inclusions in volume suddenly disrupt near the solar distance of 0.25 AU and of 0.6 AU. Since the small debris of fragmentation comes from the direction of the sun on a relatively higher eccentric orbit, this fragmentation mechanism seems favourable to explain the $\beta$-meteoroids observed at 1 AU.

## 1. Introduction

It is widely accepted that the cometary grains have at least two types of component, – i.e., refractory and icy volatile materials. The heterogeneous grain consisting of these two components is likely to exist among the cometary grains, such as core-mantle shape as proposed by Greenberg (1982).

Here we assume the presence of refractory grains with icy inclusions. Its shape is roughly sphere and small icy inclusions are embedded in a homogeneous refractory matrix. Of course, it is rather difficult to produce such heterogeneous material by nucleation of gas-mixture. We suppose, therefore, that in the early stage of the solar nebula the icy component, which is plugged up the empty space of the rough, porous, and pitted grain, was trapped by refractory material after successive collisions at a low relative velocity.

In this paper, we shall examine the process of fragmentation of such a heterogeneous grain after releasing from the comet, and show that this mechanism is favourable to explain the existence of $\beta$-meteoroids reported by Berg and Grün (1973), and Fechtig (1976).

## 2. Temperature of Heterogeneous Grain

A temperature of homogeneous grain with a spherical shape was estimated in the solar system on the basis of Mie theory (see the references in Mukai and Schwehm, 1981). The efficiency factor for absorption of the solar radiation and/or for emission of the thermal radiation from a grain, which are derived by Mie theory, depends on the complex refractive index $m^*$ of grain material. For heterogeneous material, the values of $m^*$ as a function of wavelength can be estimated on the basis of Maxwell-Garnet theory (see Bohren and Wickramasinghe, 1977).

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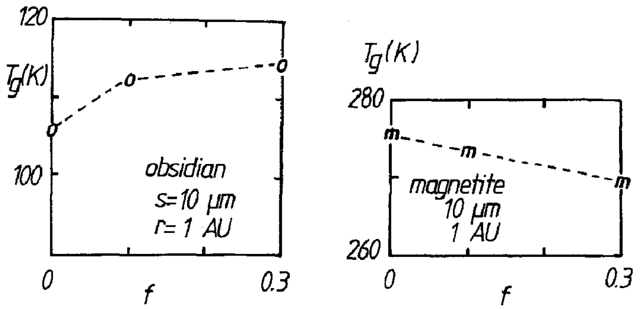


Fig. 1. Temperature of heterogeneous grain $T_g$ as a function of $f$, where $f$ denotes a volume fraction of water-ice inclusions.

We have computed the values of $m^*$ for heterogeneous grain by using those for matrix and inclusion materials, and then got the absorption/emission coefficient of heterogeneous grain by Mie theory.

It was mentioned (e.g. Mukai and Mukai 1973, Lamy 1974) that the energy loss due to sublimation plays an important role in determination of temperature of the grain $T_g$. In our grain model, icy inclusions are completely embedded in the matrix material, and therefore the sublimation of only matrix material is taken account for. The existence of icy component on the surface of grain, however, does not change our result because such volatile component quickly disappears before the grain enters the region of $T_g$ of interest, i.e. a lifetime of water-ice mantle with 1 μm-thickness is about $2 \times 10^{-6}$ s at $T_g \sim 300$ K (Mukai and Schwehm, 1981).

Equilibrium temperature of heterogeneous grain $T_g$ as functions of solar distance $r$ and grain radius $s$ is obtained by the same way as described in Mukai and Schwehm (1981). In Figure 1, we show the example of $T_g$ as a function of $f$, where $f$ means a volume ratio of inclusions to whole volume of the grain. The infrared observations of the comets (e.g. Ney, 1982) have revealed the existence of both silicate and metallic grains in the comet. Therefore, we take silicate (obsidian) and metallic (magnetite) components as matrix material of heterogeneous grain, and water-ice is assumed as icy inclusion material. The values of $m^*$ for each of above three materials are taken from the same data as used in Mukai and Schwehm (1981).

Since the presence of icy inclusions in the obsidian matrix decreases effectively the emissivity in the infrared wavelengths compared with *pure* obsidian, $T_g$ increases slightly as $f$ increases (see Figure 1a). On the other hand icy inclusions in the magnetite matrix reduce the absorption of sunlight in the visible wavelengths, then $T_g$ decreases with increasing of $f$ as shown in Figure 1b.

## 3. Fragmentation Mechanism

As a temperature of host grain $T_g$ increases, a saturation pressure $p$ of icy inclusions, which are completely surrounded by the matrix, sharply increases. We use a relation of $p$ and $T_g$ as

$$\ln p(\text{dyn/cm}^2) = -5.66 \times 10^3/T_g + 8.88 \log T_g + 7.85 \times 10^{-3} T_g + 1.12 \times 10^{-7} T_g^2 + 9.98, \quad (1)$$

where $T_g$ is in unit of K (as quoted in Mukai and Schwehm, 1981).

The saturation pressure of icy inclusions stresses the surrounding matrix material, and consequently elastic wave propagates toward the surface of grain. As mentioned by Mukai (1980), the reflected elastic wave at the surface peels off the surface layer. In addition, when super-saturation pressure exceeds a critical value $p_c$, the cracks rapidly arise around the inclusions. Then a growth of these cracks results in a fracture of host grain (see Selberg, 1952).

In order to do quantitative discussion in more detail, further investigations about these complex processes are necessary. In this paper, however, we simplify the problem, and assume that a catastrophic fracture of a heterogeneous grain occurs when $p \geqq p_c$.

## 4. Results and Discussion

The values of $p_c$ are estimated from typical values of the crack-extension-force necessary for onset of unstable fast fracturing (Tetelman and McEvily, 1967), referring the strengths of both obsidian and magnetite used in Mukai (1980). That is, $p_c = 8 \times 10^9$ dyn/cm$^2$ for obsidian and $1 \times 10^{10}$ dyn/cm$^2$ for magnetite.

Putting these values of $p_c$ into Equation (1), we can estimate the region of temperatures of host grain where $p = p_c$, i.e. 400 ~ 500 K for both matrix materials. Due to a lack of reliable data for thermodynamical behaviour of water-ice under such high pressure and high temperature (type VII water-ice; see Fletcher, 1970), we assumed that Equation (1) still holds in these limited conditions. Consequently, it is derived from a dependence of $T_g$ on the solar distance computed in Section 2 that the fragmentation of heterogeneous grain happens in the shaded region in Figure 2.

It is worthwhile to mention that the debris of the fragmentation should take higher eccentricities $e$ of orbits when they cross the Earth's orbit. This arises from the fact that a higher probability of fracture occurs for heterogeneous grain with smaller perihelion distance $q$: namely, the grain should enter the shaded region in Figure 2 to disrupt.

Figure 3 shows an observable region of fragmentation debris in the $(q, e)$ space at 1 AU. This implies that the small debris produced by fragmentation of heterogeneous grains with $s = 100\,\mu$m comes from a direction of the Sun, and it is likely to exist in the probable region in the $(q, e)$ space, where the eccentricity of the orbit is relatively higher, among the whole grains which cross the Earth's orbit.

An increase of relative radiation pressure on the debris is likely to push smaller grain to higher eccentric orbit compared with the orbit of parent heterogeneous grains. Furthermore a part of such smaller grains might be blown off on hyperbolic orbits as discussed about the submicron-sized grains ejected by the comets (Mukai *et al.*, 1983). Then the existence of results smaller grains on higher eccentric orbits seems favourable to explain the observed $\beta$-meteoroids near the Earth.

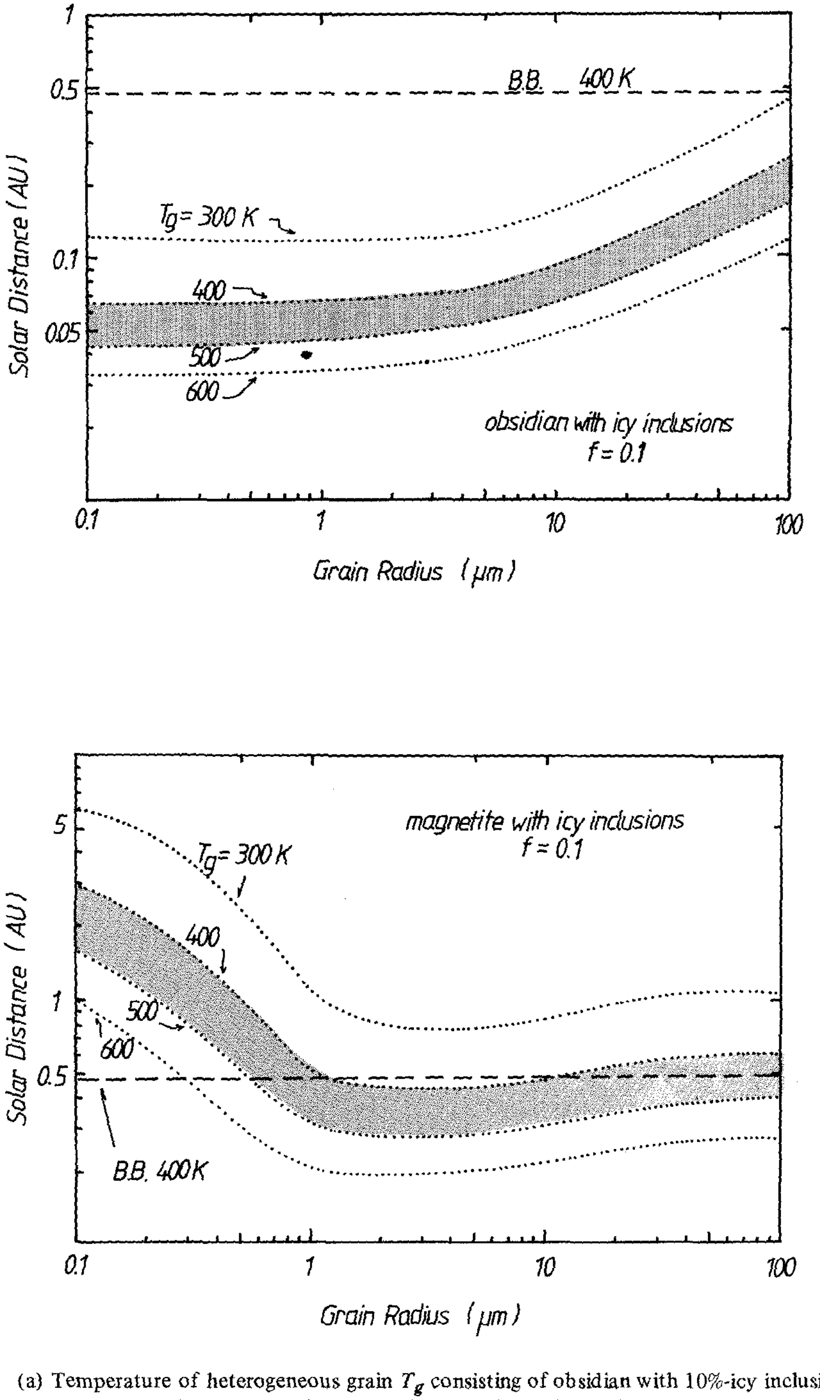


Fig. 2. (a) Temperature of heterogeneous grain $T_g$ consisting of obsidian with 10%-icy inclusions in volume ($f = 0.1$), as functions of solar distance and grain radius. The shaded region represents a probably area, where the evaporation breakup of heterogeneous grain occurs. B.B. means a temprature of black body. (b) The same as (a), except for magnetite instead of obsidian.

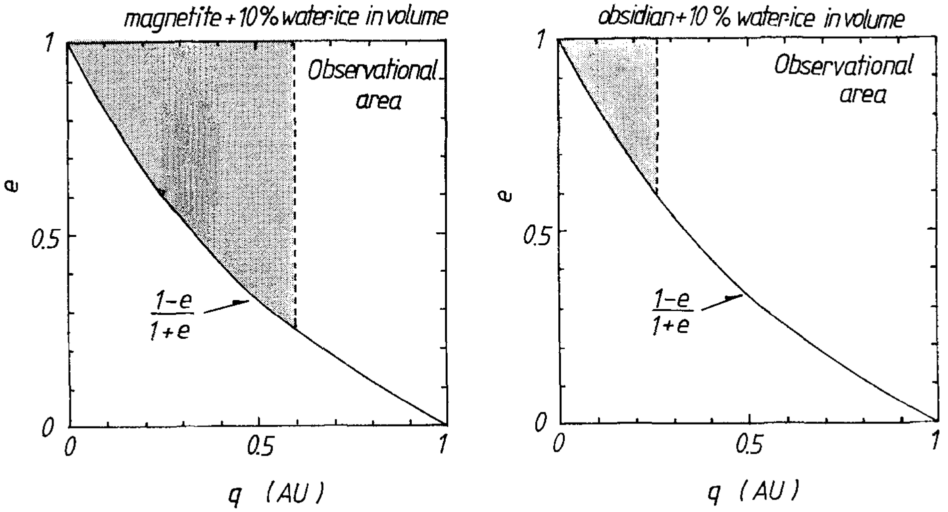


Fig. 3. Observational area means the region corresponding to orbits crossing the position of an observer with a solar distance of 1 AU, where $q$ is a perihelion distance and $e$ denotes an eccentricity of the orbit. The fragmentation debris of heterogeneous grain with radius of 100 $\mu$m has the $(q, e)$ values in the shaded region.

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## References

Berg, O. E. and Grün, E.: 1973, *Space Research* XIII, 1047.
Bohren, C. F. and Wickramasinghe, N. C.: 1977, *Astrophys. Space Sci.* **50**, 461.
Fechtig, H.: 1976, *Lecture Notes in Physics* **48**, 143.
Fletcher, N. H.: 1970, *The Chemical Physics of Ice*, Cambridge Univ. Press, Chap. 3.
Greenberg, J. M.: 1982, in L. L. Wilkening (ed.), *Comets* The University of Arizona Press, p. 131.
Lamy, Ph. L.: 1974, *Astron. Astrophys.* **35**, 197.
Mukai, T.: 1980, in I. Halliday and B. A. McIntosh (eds.), *Solid Particles in the Solar System*, D. Reidel Publ. Co., Dordrecht, Holland p. 385.
Mukai, T. and Mukai, S.: 1973, *Publ. Astron. Soc. Japan* **25**, 481.
Mukai, T. and Schwehm, G.: 1981, *Astron. Astrophys.* **95**, 373.
Mukai, T., Mukai, S., Schwehm, G., and Giese, R. H.: 1983, in T. I. Gombosi (ed.), *Cometary Exploration*, Vol. II, p. 135.
Ney, E. P.: 1982, in L. L. Wilkening (ed.), *Comets* The University of Arizona Press, p. 323.
Selberg, H. L.: 1952, *Ark. Fys.* **5**, 97.
Tetelman, A. S. and McEvily, Jr. A. J.: 1967, *Fracture of Structural Materials*, John Wiley and Sons, Inc..