GRAIN DISRUPTION BY COLLISIONS WITH SOLAR ENERGETIC PARTICLES

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Abstract. The catastrophic disruption of interplanetary dust grains, including water-ice, obsidian and magnetite, by impinging solar cosmic rays is investigated. The disruption is caused by the stress wave emanating from the heated lattice atoms along the path of an impinging particle. We find that the disruption plays an important role in the mass loss rate of grains compared with that due to sublimation and sputtering by solar particles.

1. INTRODUCTION

An interplanetary dust grain loses its size gradually by sublimation and/or sputtering by solar energetic particles. On the other hand, it suffers catastrophic disruption due to such mechanisms as rotational bursting (Paddack 1969) and electrostatic disruption (Rhee 1976). We propose here another disruption mechanism caused by impinging solar particles associated with large flare events. That is, the induced stress wave inside the grain produces disruption just like that of planetesimals by high velocity impact recently discussed by Fujiwara (1979).

2. DISRUPTION MECHANISM

An impinging charged particle, a proton or an α-particle, makes a cylindrical heat tube along its path in the grain material (water-ice, obsidian and magnetite are considered here). The lattice atoms in the heat tube should exert a pressure on the surrounding medium as shown by Seitz and Koehler (1956). The magnitude of the pressure p at the boundary of the heat tube is estimated as follows: the radial displacement u(r) about the cylindrical region of radius r_0 is given by $u(r)=(2\mu)^{-1}(r_0^2/r)p$, ($r \geq r_0$) (Love 1944) where r is the radial distance from the axis of the cylinder and μ is the shear modulus of the grain material. Then at $r=r_0$, $p=2\mu u(r_0)/r_0=2\mu\alpha\Delta T$, where α is the coefficient of thermal expansion and ΔT denotes the difference in temperatures between those of the heat tube and of the surrounding medium.

I. Halliday and B. A. McIntosh (eds.), Solid Particles in the Solar System, 385–389.

Based on Mukai and Schwehm (1979) (hereafter MS), we get $\Delta T=1.36\ 10^{-6}\ (\pi r_0^2 C_v)^{-1}\gamma|dE/dx|$ and $|dE/dx|=\rho((A\ \ln E/E)+B/E)$ where C_v is the specific heat per unit volume (in units of erg $cm^{-3}K^{-1}$), γ is the conversion efficiency of electronic energy to lattice energy ($0<\gamma<1$), $|dE/dx|$ is the energy loss rate of a particle with energy E (in MeV) per unit path length (in MeV cm^{-1}), ρ is the mass density of grain material (in g cm^{-3}), and A and B are constants (see MS).

The duration of the pressure t_p is the same order as the cooling time of the heat tube, i.e. $r_0^2 C_v(4\kappa)^{-1}$ where κ is the thermal conductivity of the grain material. Since t_p takes a value of the order of 10^{-13} sec, a displacement spike caused by the pressure on the surrounding material behaves as an extremely short pulse.

This stress pulse propagates in the grain material and its amplitude decreases as the radial distance increases. According to Selberg (1952), the radial stress (compressive stress) σ_r is given by $\sigma_r=(r_0/r)^{\frac{1}{2}}p$ in $r_0/r<<1$. It is worth noting that since the pulse has a sharp form, the highly damped behaviour of wave amplitude shown by Selberg can be neglected here. It is known, furthermore, that considerable tensional stress will rapidly arise in the tangential direction, i.e. σ_T, even though the initial pressure has only a radial component. Consequently, if the stresses of σ_r and/or σ_T exceed the critical strengths of grain material at $r=r_0$, a radial system of cracks around the heat tube would appear as mentioned by Selberg. We are, however, interested in the mass loss from the surface of the grain, therefore the appearance of cracks will not be discussed here even though it remains a possibility that the growth of cracks causes grain fracture.

When the stress pulse reaches the surface of the grain with sufficient magnitude, it is reflected as a tensile wave. Since the tensile strength of a material, in general, is very weak compared with its compressive strength, then fracture occurs abruptly, and the surface layer of the grain flies off. Therefore, we can define the maximum radius s_{max}, above which disruption of the surface layer cannot occur as $s_{max}=r_0(p/S_s)^2$, where S_s is the tensile strength of grain material. In order to derive the induced pressure p, we use $\gamma=0.72$, $r_0=2\ 10^{-7}$ cm (see MS) and the values of parameters listed in Table 1. Figure 1 shows the values of s_{max} as a function of the proton energy. For simplicity, we assumed that an impinging particle passes through the grain center.

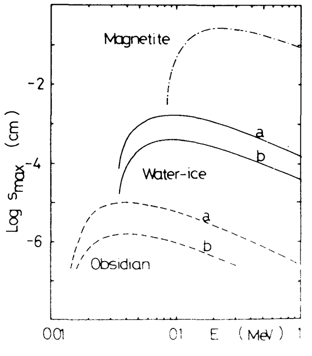

Fig. 1. Maximum grain radius s_{max}, above which disruption does not occur, vs. the proton energy. The a and b in water-ice and obsidian correspond to a tensile strength (in 10^8dyn cm^{-2}) of (1.0, 2.0) and (2.8, 6.9), respectively.

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Table 1. Values of the physical parameters

	ρ	A	B	C_v^*	κ*[1]	α	μ	S_s	v
water-ice	1	80.4	276	8.42	6.51	12*[2]	0.45*[5]	1.0*[7] 2.0*[8]	4.21*[12]
obsidian	2.4	72.3	309	5.96	2.08	0.55*[3]	3.00*[6]	2.8*[9] 6.9*[10]	5.82*[6]
magnetite	4.8	68.5	172	2.05	4.14	24*[4]	2.10*[6]	0.48*[11]	4.07*[6]

$\rho(\mathrm{g\ cm^{-3}})$, $C_V(10^6\mathrm{erg\ cm^{-3}K^{-1}})$, $\kappa(10^5\mathrm{erg\ sec^{-1}cm^{-1}K^{-1}})$, $\alpha(10^{-6}\mathrm{K^{-1}})$, $\mu(10^{11}\mathrm{dyn\ cm^{-2}})$, $S_s(10^8\mathrm{dyn\ cm^{-2}})$ and $v(\mathrm{km\ sec^{-1}})$

References and comments: *[1] see the references in Mukai and Schwehm (1979) *[2] TPRC vol. 13 (1977) p. 261 *[3] American Ins. Phys. Handbook (1963) 4-71 *[4] TPRC vol. 13 (1977) p. 278 *[5] Fletcher (1970), a 20% increased value concerning the temperature effect *[6] Anderson and Liebermann (1968), from $\mu=\rho v_0^2$, v_0 is a shear sound velocity *[7] Dykins (1969), a 20% increased value of his horizontal strength *[8] ibid, that of his vertical strength *[9] Corrosion Handbook ed. H.H. Uhling (1948) (John Wiley & Sons. Inc.) p. 356, vitreous silica *[10] used in Paddack (1969), tektite glass *[11] Machinery's Handbook 18th ed. (1968) (Industrial Press Inc.) p. 432, granite *[12] from $\rho v^2=\lambda+2\mu$, λ and μ are Lame's constants.

3. MASS LOSS RATE OF GRAIN

The mass loss rate per unit surface of a grain with radius s due to disruption is expressed by $dM/dt=\int_{E_{min}}^{E_{max}} J(E)dE\pi s^2\rho\Delta s$, where the differential energy flux of solar cosmic rays is approximated by $J_p(E)=2.5\ 10^5$ protons $\mathrm{cm^{-2}sec^{-1}sr^{-1}MeV^{-1}}$ at 1 a.u. (Lin and Hudson 1976), and a ratio of fluxes J_α(1MeV/nucleon)/J_p(1MeV) is assumed as 0.03 (Lanzerotti et al. 1978). The Δs is the thickness of the peeled-off layer, which is the same order as the width of the stress pulse, i.e. $t_p v$, where v is a wave velocity inside the grain. The values of E_{min} and E_{max}, both of which depend on s, are derived using figure 1.

In order to compare dM/dt by disruption with that by sputtering, we multiply by a factor of $3\ 10^{-4}$, which is concerned with the number of flare events (see MS), with dM/dt by disruption. Furthermore, the values of dM/dt by disruption would be reduced by a factor of $\underline{l}/s$ when $s>\underline{l}$, where $\underline{l}$ is a path length before a particle stops. For simplicity, although $\underline{l}$ depends on the energy of the impinging particle, we use here a constant value of $\underline{l}$, i.e. $\underline{l}=2\ 10^{-4}$cm in water-ice, 10^{-4}cm in obsidian and 10^{-3}cm in magnetite (see the derivation of $\underline{l}$ in MS).

Figure 2 presents the mass loss rate of a grain at 1 A.U. due to disruption, that due to sputtering by solar wind particles and that due to sublimation in only water-ice. The sputtering is derived (see MS) in the minimum, average and maximum phases of solar wind. These phases have the values of (flux in units of particles $\mathrm{cm^{-2}sec^{-1}}$, flow velocity in km $\mathrm{sec^{-1}}$); (10^8, 200), (3×10^8, 400) and (10^{10}, 900), respectively.

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Since the sputtering due to solar cosmic rays plays a minor role as shown in MS, we neglect its contribution to dM/dt.

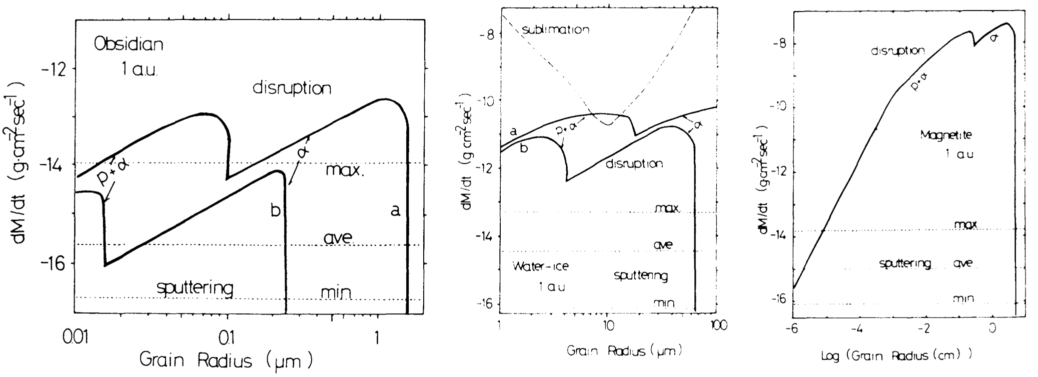

Fig. 2. Mass loss rate per unit surface of grain at 1 A.U. In disruption, p+α means the contribution of both proton and α-particle in contrast with α, that of only α-particle. In sputtering, max., ave. and min. denote the phases of solar wind as shown in the text. Note the change of scale in grain radius of magnetite.

An α-particle with the same velocity as a proton causes an induced pressure four times larger than that produced by the proton because $|dE_\alpha/dx|=4|dE_p/dx|$, where $E_\alpha=4E_p$ (Whaling 1958). Then, s_{max} due to an α-particle is 16 times larger than that due to a proton. Therefore, in figure 2 there are two critical grain radii above which the contribution of disruption to dM/dt disappears.

From figure 2, we get the following results:
(i) for obsidian, the disruption has an influence on the mass loss rate of grains with radius less than about 0.1-1 μm. Below s=0.01 μm, however, sputtering dominates disruption, and
(ii) for both water-ice and magnetite, compared with sputtering, disruption plays an important role in the mass loss rate of a grain with radius larger than about 0.1 μm. However in water-ice at 1 A.U., sublimation controls the mass loss rate of the grain.

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Singer: Aren't we dealing with an energy range well beyond sputtering? An incident 1MeV proton will give up its energy initially to the electrons of the target. The question is what fraction is communicated to the lattice energy? Especially if we are dealing with a (more-probable) non-central impact.
Mukai: The conversion efficiency, γ, of electronic to lattice energy does not depend on the position of the heat tube in the grain. I took $\gamma=0.72$ based on a comparison of the sputtering rate derived by an evaporation model with the rate based on experimental results from water-ice (see Mukai and Schwehm 1979).

Hughes: If you have hypervelocity impacts, isn't the shock pulse velocity in the grain highly supersonic? If so, don't you get more disruption?
Mukai: For simplicity I did not consider the possibility of a supersonic shock in the grain.

Misconi: You used tensile strengths of the order of 10^8 or 10^9 dyne/cm^2. Have you considered the effect of your mechanism on particles of much lower tensile strength, by say orders of magnitude like fragile or very porous particles?
Mukai: Yes. As the tensile strength of the grain material decreases, in general this disruptive mechanism becomes more effective compared with sputtering.

Cook: Are there any experiments on sputtering which can be used to check these computations?
Mukai: No. But the disruptive mechanism which is caused by induced stress inside the grain is just like the disruption of planetesimals by high velocity impact as discussed recently by Fujiwara (1979). I think his experimental work is useful in this examination of the disruption problem.

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