EXISTENCE AND ROLE OF AMORPHOUS GRAINS IN THE SOLAR SYSTEM

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Consideration of the nucleation and growth processes and observational arguments suggest that besides crystalline grains in the solar system and interplanetary space there are also amorphous H_2O-ice, SiO_2 and C grains. Of particular importance are effects of the bombardment of these grains by protons in the solar wind and in the planetary radiation belts and the ensuing various erosion processes. Differences in the physical properties of crystalline and amorphous grains lead to interesting astrophysical consequences.

1. AMORPHOUS GRAINS

Although small particles in the solar system made of water ice, graphite or silicates, are certainly not crystallographically perfect it is usually assumed that their defects such as atomic vacancies, interstitials, dislocations, chemical impurities and deviations from stoichiometry, play only a secondary role. This point of view is not tenable for amorphous grains whose existence is suggested by the nucleation and growth processes occuring at temperatures which are too low to permit sufficient surface mobility of the adsorbed atoms or molecules (H_2O, SiO_2, C, C_2, C_3, C_6, etc.) to form regular lattices. Experiments show that for water ice the approximate limiting temperature is 150°K, for SiO_2 1000°K and for carbon about 1500°K. Such conditions can exist in the solar or protoplanetary nebulae and in the circumstellar clouds. Important here are also the surface energies and the degree of supersaturation in the vapor phase (Tabak, *et al*. 1975, Donn 1978). Further direct or indirect arguments for the existence of amorphous grains are various observations (Day and Donn 1978, Smoluchowski 1979a) and in particular the observed non-crystalline grains in clusters of small extraterrestrial particles (Brownlee *et al*. 1980).

In amorphous solids the atoms are arranged at random, that is, each atom has a sufficient number of neighbors to keep it in place, but the resulting structures do not have long or short range symmetry. In carbon the randomness is rather characterized by an irregular (turbostatic) stacking of imperfect and corrugated two-dimensional layers (Ergun 1968).

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From the point of view of interaction with gases in the solar and protoplanetary nebulae (Smoluchowski 1979a) it is important to note that while amorphous SiO_2 and ice (and ice clathrates) can exist with no atomic defects (tetrahedral coordination preserved although the angles between bonds are altered) amorphous carbons appear to have many atomic defects and pores of the order of 4-20Å (Rivin 1971).

2. INFLUENCE OF RADIATION

Bombardment of solid particles by protons, ions and electrons of the solar wind and especially in the Van Allen belts is of crucial importance for their structure and lifetime. In this respect protons are more important than ions or electrons because the flux of the former is low and most of the latter have such high energies that they lose very little of it upon passage through a small solid particle. The maximum rate of energy loss of a proton occurs in fact within a factor of 5 or so at 100 keV for solids of interest. The effect of solar wind protons, which have an energy of a few keV, is confined to a surface layer 0.1 to 1μ thick. The flux of protons in the Jovian radiation belt is proportional to $E^{-\frac{1}{2}}$ so here too the low energy component plays the main role. A proton incident upon a conductor (graphite or metal) produces displaced atoms and vacancies by collisions while in an insulator the damage is much higher because then additional displacements may result from ionization. In initially crystalline solids radiation leads to local disorder through atomic displacements and localized heating. In amorphous solids, or in highly imperfect crystalline solids, on the other hand, a similar increase in the concentration of defects and in the effective local temperature results in an increased rate of diffusion which in turn may decrease the degree of metastable disorder. Eventually this radiation annealing is balanced by the production of new defects and, ideally, a certain equilibrium state of disorder corresponding to the intensity of the radiation field sets in. A rough estimate of rates of these processes suggests that the degree of lattice disorder thus produced in crystalline solids, for instance by the solar wind may approximate that present in amorphous solids but that the parallel progressive crystallization of amorphous solids is limited to a small fraction of their volume (Smoluchowski 1978).

3. EROSION

When the collisions and displacements occur near the surface of solids then individual atoms or molecules will be sputtered away. Estimates of this important process (Draine and Salpeter 1979) give maximum yields per incident proton of about one H_2O molecule for ice, $3x10^{-2}$ carbon atoms for graphite and $3x10^{-2}$ $MgSiO_3$ molecule for this silicate. This yield should be about the same for crystalline and amorphous grains. On the other hand if the solid, such as ice, has a rather low melting temperature the sputtering is orders of magnitude more efficient than that due to individual collisions and is better described as evaporation from the thermal spikes (Bøttiger *et al.*1979) which are regions along the path of the particles in which the instantaneous temperature is very high. Since the thermal conductivity of amorphous solids at low temperatures may be 10^2 - 10^3 times lower than that of crystalline solids the duration of the high temperature along the thermal spike in amorphous grains is correspondingly longer and the erosion should be more pronounced. In any case the sputtered or evaporated atoms and molecules may condense back on the same or other grains and form amorphous layers if, as mentioned above, the temperatures are low enough. Sputtering of graphite at temperatures above 600°K by protons is very high but it leads primarily to the formation of CH_4 (Roth *et al.* 1976).

Thermal spikes have another important consequence which arises from the fact that an instantaneous heating leads to rapid local expansion which, if not accommodated elastically by the surrounding cold lattice, will result in a local fracture. A detailed analysis of this process shows that the shear stress produced at the center of a high temperature thermal spike in H_2O, SiO_2 and graphite can be of the order 4×10^9, 2×10^{10} and 2×10^{11} dynes cm^{-2} respectively which is higher than the strength of these solids. This stress falls off exponentially with time and as r^{-3} with distance but since upon cooling the local plastic deformation is, in general, not reversible the damage is cumulative and the resulting mechanical fatigue will lead to local fracture. If this damage occurs near the surface then any subsequent erosion resulting from interparticle collisions is greatly enhanced. This effect is probably the most important irradiation effect produced by the solar wind and by the slow radiation belt protons which, as mentioned above, have a high flux and a very short range in the solid. Again, this kind of erosion would be higher on amorphous than on crystalline grains. It has been suggested that this mechanism is responsible for the disc extending between Jupiter and its ring (Smoluchowski 1979c). Also, it is probably more important in affecting the cometary nuclei and cometary dust than purely collisional processes (Whipple 1977).

4. OTHER CONSEQUENCES

The protons of Saturn's Van Allen belt should sputter the outer edge of the A-ring (Cheng & Lanzerotti 1978) as well as the nearby new F-ring, if its opacity is indeed very low and the escaping H_2O molecules would then form an amorphous ice coating on the inner Saturnian rings (Smoluchowski 1978). The interparticle collisions in the rings undoubtedly produce a considerable concentration of very small ice grains which, if crystalline, should produce a halo around the sun at a phase angle of about 158°. Detection of this effect by a spacecraft would be an argument against the above mentioned sputtering and re-deposition of amorphous ice. Only weak sputtering would be expected on the so-called G-ring because the planet probably does not have a magnetodisc and thus the magnetic field and the radiation belt at a distance of 12 ± 2 planetary radii is weak.

The difference in the electronic structure should lead to an increased probability that amorphous solids are ionized by ultraviolet radiation and thus small amorphous grains would be more likely positively charged, interact with gaseous ions and be affected by a magnetic field

(Mendis and Hill 1980). This may even result in a spatial separation of amorphous and crystalline grains.

Amorphous and highly imperfect solids have a low mechanical Q factor which is important in certain aspects of suprathermal rotation of grains. (Purcell 1979).

The Yarkowski effect which is a force acting on rotating illuminated meteorites (Peterson 1976) would be weaker for particles which are amorphous or are coated with amorphous layers. The much lower thermal conductivity would speed up the heating and the cooling process and decrease the time lag between illumination and thermal effects.

As far as amorphous grains in the interstellar space are concerned their presence would have important consequences for the formation of H_2 and other molecules because of the drastically reduced surface mobility of the adsorbed atoms (Smoluchowski 1979a, b).

It seems that the best indication whether amorphous solids are abundant in the solar system or not will come from studies of their optical absorption especially in the IR region and from direct observation of Brownlee grains.

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