5.10

ARE INTERPLANETARY GRAINS CRYSTALLINE?

S. Drapatz and K.W. Michel
Max-Planck-Institut für Physik und Astrophysik
Institut für extraterrestrische Physik
8046 Garching, W.-Germany

Abstract: The optical properties of interplanetary grains depend not only on chemical composition, size, and shape but also on lattice defects. It is argued that practically all sources for the zodiacal dust cloud yield grains with highly disturbed crystal structure. Healing of these defects can occur when the grains are heated in the vicinity of the sun ($\lesssim$ 0.1 AU) and various orbits are considered, on which annealed grains with nearly perfect crystal structure can return to larger heliocentric distances to reveal the sharp optical features of cold well-ordered crystals. However, we do not find any processes, which produce healed particles of sufficient number to affect the properties of the general zodiacal cloud. Therefore, the optical properties of interplanetary grains are determined by a high degree of lattice perturbation.

1. Introduction

As is well known, there can exist a great difference in the absorption coefficients ($\alpha = 4\pi k\tilde{\nu}$) of the same material if the degree of lattice perturbation is different, as can be seen for silicates (Fig.1).

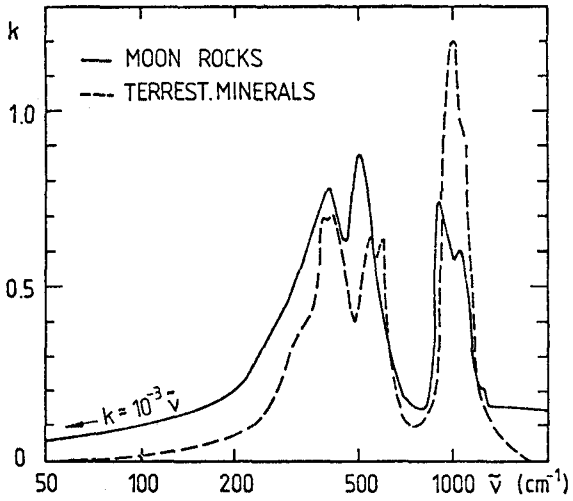

Fig. 1: Extinction coefficient k of silicates with high (moon rocks) and low (terrestrial minerals) degree of lattice perturbation. Averaged moon rock data shown here correspond to samples with low plagioclase content (PERRY et al. 1972). Terrestrial mineral data are taken from POLLACK et al. (1973) and HUFFMAN (1975).

So, for the thermal emission of grains and correlated temperature distribution the question is important, whether grains are well ordered or disturbed, e.g. by radiation damage. Their structure is also important in the investigation of the linear and circular polarization. To investigate the structure of grains the knowledge of processes is necessary that create or destroy crystal structures, viz. which transform well-ordered crystalline structures into disturbed lattices with defects, and vice versa. If material exists in an amorphous phase annealing is possible by recrystallization, i.e. defect-free grains grow within the old deformed ones if roughly $T > \frac{1}{2} T_{melt}$ (Wigley 1971) or if the material melts and cools slowly ($\Delta T/\Delta t < 1$ K/h, SCHOTT 1971). In addition a disturbed lattice may be partly healed by diffusion of point defects (vacancies and interstitials) or impurities to the surface (at $T >$ some 100° K). On the other hand radiation damage destroys crystal structures by generation of point defects inside the crystal and sputtering at its surface. Crystals with high defect concentration, amorphous grains and highly heated grains have similarly smeared out and diffuse optical properties, whereas well-ordered crystals show often distinct, sharp absorption and emission features. Hence, close to the sun we expect disordered grains. Perturbed grains can gain sharp bands if they return from the solar vicinity to larger heliocentric distance where they cool. As opposed to well-ordered crystals, the optical properties of perturbed grains show little dependence on temperature.

The question whether the interplanetary grains are well ordered now depends on the answer to the following problems:

- What are the sources of interplanetary grains and do they supply crystalline or highly perturbed material?
- What are the orbits of the grains and can one of the mentioned healing processes occur, while the grain moves on its orbit?

2. The sources of interplanetary grains

The possible sources of interplanetary grains are "primary" ones: interstellar medium, asteroidal belt, comets, primordial debris, and "secondary" sources, which change the size and orbit parameters of primaries or generate secondaries: gravitational force of planets (esp. Jupiter, VAGHI 1973), rotational bursting, collisional break-up (ZOOK and BERG 1975), evaporation (LAMY 1974), impact on planets or their satellites (mercury, moon).

The crystal structure of primary particles of all sources is probably highly perturbed. The interstellar and primordial debris (high orbital inclination) grains were exposed to cosmic rays, which cause high defect concentration (ratio of density of point defects to density of atoms in the grain $n_d/n_o > 0.01$ for some 10^6 y exposure time to interstellar 2 MeV-protons with a flux of 10^2 cm^{-2} sec^{-1}). The comets probably have been formed at temperatures $250 < T < 400$ K (Biermann 1975) in the presolar nebula at distances beyond Jupiter's orbit. When orbiting around the sun at $R > 4$ AU, the internal temperature does not rise beyond $T = 280/\sqrt{R} < 140$ K (no defect healing). As far as asteroidal grains are concerned, only the inner regions of larger (> 1 μ) grains may be crystalline, in spite of the solar wind sputtering and surface erosion, since the penetration depth for 1 keV-protons is low ($\lesssim 0.1\ \mu$ in quartz, Hines 1960). The question arises, is there an appreciable fraction of these particles moving around the sun on elliptic orbits with eccentricities high enough that they approach the sun and are heated above $T = \frac{1}{2} T_m$ (corresponding to perihelion distances of $q \approx 0.1$ AU) and that they still have semi-major axis $a > 0.5$ AU to contribute noticeably to the interplanetary dust.

a) Interstellar particles: An interstellar particle (particle radius a_s, velocity $v_\infty = 20$ km/sec outside the heliosphere) will be captured into an elliptic orbit, if the change Δe of the eccentricity e of the initially hyperbolic orbit during one revolution due to radiation pressure is $\Delta e > e - 1$. Particles with $a_s \lesssim 0.1\ \mu$, where solar wind pressure and Lorentz force are dominant (ELSÄSSER 1967) are not considered. The formula below gives perihelion distances q for the particles of maximum impact parameter for capture (≈ 0.1 AU, at particle sizes $a_s \approx 0.7\ \mu$)

$$q \approx R_\odot \left(\frac{20\ \mathrm{km\ sec}^{-1}}{v_\infty}\right)^{-4/3}$$

For defect annealing and to avoid vaporization q has to be in the range $10\ R_\odot < q < 20\ R_\odot$, which seems to rule out this source.

b) Comets: The perihelion distance of bright periodic comets (see e.g. compilation by ALLEN 1973) is $q = a(1-e) > 0.3$ AU. Since the change of the eccentricity $\frac{de}{dt}$ is much faster than change of the semi-major axis $\frac{da}{dt}$, these particles will not move in highly eccentric orbits ($q \lesssim 0.1$ AU), if no perturbation of the orbit other than Poynting-Robertson effect occurs. In addition it has been emphasized by HARWIT (1963) that most cometary dust grains will leave the solar system in hyperbolic orbits.

c) Asteroids: If particles are generated by asteroidal collisions and grinding, their relative velocities (some km sec^{-1}, G.W. WETHERILL 1968) will be smaller than the orbit velocity of asteroids ($\approx 1.8 \cdot 10^6$ cm sec^{-1} at 2.8 AU). Then the eccentricity of the particle orbit is roughly

$$e = \left[\left(1 - \frac{v_\perp^2 r}{\mu}\right)^2 + \left(\frac{v_\parallel v_\perp r}{\mu}\right)^2\right]^{1/2} \approx 1 - \frac{v_\perp^2 r}{\mu}$$

where $\mu = GM_{\odot} - \alpha c$ the usual solar gravitational constant decreased by radiation pressure and $v_{\perp}$, $v_{\parallel}$ are the particle velocities relative to the sun-asteroid vector **r**. In order to obtain perihelion distances q 0.1AU a serious perturbation of the orbit has to occur by other than radiation pressure forces which is very unlikely as has also been shown by DOHNANYI (1976).

3. The change of particle orbits and sizes

Particles of asteroidal or cometary origin may be deflected into Mars-crossing orbits and then by Mars into Earth-crossing orbits etc. But even these multi-step processes yield eccentricities too low for $q < 0.1$ AU to occur (WETHERILL 1967). Also "secondary" particles can be generated by impact of primaries on moon or mercury. Take the moon as an example. If lunar material (density ρ_m) is hit by meteorites (density ρ'_m , velocity $w \approx 30$ km $\sec^{-1}$) then the velocity u of emitted particles (DRAPATZ and MICHEL 1974) is

$$u = w\left(\sqrt{\frac{\rho m}{\rho m'}} + 1\right)^{-1/2} \approx \frac{w}{\sqrt{2}}$$

Neglecting in a rough approximation the perturbation of the particle's orbit by the earth and the relative velocity of earth and moon with respect to the earth's orbiting velocity, one finds that for particle radii $a_s \gtrsim 1\ \mu$ the fraction of ejected particles that can become crystalline is $f \approx 0.1$, but considerably smaller for smaller w (see also GAULT 1964).

Inside $r = 20\ R_{\odot}$ particles' mass (and hence orbit) may be drastically changed by evaporation of particles or collisional break-up. While the first process (investigated by LAMY 1974) leads to disappearance of particles, the second process might be important and has been considered in another context by ZOOK and BERG (1975). On the basis of their derivation particles with masses $1 - 10^{-5}$ g suffer a catastrophic collision at $r \lesssim 0.2$ AU (where relative velocities of particles and spatial densities are quite high). The collision debris are small enough for radiation pressure to change the orbit significantly. Particles spiral inside an orbit R for a maximum ratio β_{max} of radiation force to gravitational forces

$$\frac{\beta max - 0.5}{(r_i/R)^2} - \frac{\beta max - 1}{r_i/R} = \frac{1}{2}$$

if the meteorites' initial circular orbits have radius r_i, and the debris has zero velocity relative to one of the colliding bodies. Therefore, a considerable fraction of the smaller particles can reach larger heliocentric distances (e.g. $R = 0.6$ AU for $r_i = 0.1$ AU and $0.5\ \mu$ particles).

Nevertheless, the contribution of these particles to the mass of the general zodiacal cloud is negligible.

4. Summary

We do not find any processes in interplanetary space which return grains, whose defect concentration has been reduced in the solar vicinity, to larger heliocentric distance with sufficient efficiency, to affect the properties of the general zodiacal cloud. Thus, the imaginary part of the refractive index (related to the extinction coefficient by $\alpha = 4\pi k\tilde{\nu}$) shown for disturbed lunar rocks in Fig. 1 might be recommended also for interplanetary grains. Unfortunately, optical properties of radiation damaged silicates have not yet been determined for the visible spectrum. The extinction coefficients, known for well-ordered terrestrial materials, would imply an absorption of less than 1 % of the incident solar radiation for particles of size $a_s = \lambda/2\pi$, whereas much higher absorption and as consequence higher grain temperatures are expected for more realistic perturbed crystals. Finally it should be mentioned that lattice defects are also important for interstellar grains (DRAPATZ and MICHEL, 1975).

5. References

Allen, C.W.A., Astrophysical Quantities, Athlone Press (1973)
Biermann, L., private communication (1975)
Dohnanyi, J.S., this volume, 1976
Drapatz, S., and K.W. Michel, Z. Naturf. 29a, 870 (1974)
Drapatz, S., and K.W. Michel, Workshop on Interstellar Grains, Gregynog Hall, Wales (1975)
Elsässer, H., NASA SP-150 p. 287 (1967)
Gault, D.E., et al., NASA TN D-1767 (1963)
Harwit, M., J. Geophys. Res. 68, 2171 (1963)
Hines, R.L., Phys. Rev. 120, 1626 (1960)
Huffman, D.R., private communication (1975)
Lamy, Ph.L., Astr. Astrophys. 33, 191 (1974)
Perry, C.H., et al., The Moon 4, 315 (1972)
Pollack, J.B., et al., Icarus 19, 372 (1973)
Schott, "Schott-Zerodur", Mainz (1971)
Wetherill, G.W., J. Geophys. Res. 72, 2429 (1967)
Wigley, D.A., "Mechanical Properties of Material at Low Temperatures" Plenum Press N.Y. (1971)
Vaghi, S., Astron. and Astrophys. 24, 107 (1973)
Zook, H.A., and O.E. Berg, Planet. Space Sci. 23, 183 (1975)