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SURFACE PHENOMENA IN SIMULATED COMETARY NUCLEI

O. V. DOBROVOLSKY AND E. KAJMAKOV

The sublimation or artificial icy cometary nuclei with different inclusions is investigated. Formation of meteoroids is discussed in connection with new polarizational observations of comet West. The possibility of chemical reactions on the sublimating surface is noted.

1. At this colloquium we enjoyed beautiful chain structures which probably formed spontaneously in ancient times by condensation. From the standpoint of comet and meteor investigators the question is whether such or similar structures could originate or are originating in cometary nuclei as sources of meteor matter.

One of the approaches to this problem is laboratory simulation of cometary nuclei. A great number of such experiment have been performed at the Joffee Physical-Technical Institute in Leningrad and at the Institute of Astrophysics in Dushanbe too.

A part of the experiments involving sublimating water ices with different inclusions is described below.

2. Inclusions not solvable in water (metallic particles, grains of Al_2O_3, $Si\ O_2$ etc.) [1,3,5,6].

2.1 High energy flux. Sublimation proceeds as in pure ice; all not too great inclusions go away with the sublimating gases.

2.2 Low energy flux. The less volatile components form a surface layer or matrix through which the sublimating gases are flowing. High concentrations, small particle densities and sizes facilitate the crust formation. Growing gas pressure beneath the matrix breaks it up, and fragments of the matrix -- conglomerates of some tens or hundreds of initial particles -- flow away with the outgoing gas. Figure 1 represents an example of such matrix fragments. The initial particles were 2 micron Ni grains with initial concentration C_{vol} = 0.35%. The temperature T was 71.6^o C below zero. The largest fragments consist of hundreds of initial grains. After the outburst a new crust is formed and the conditions for a new outburst are restored. The period P and the thickness h of the matrix by the moment of the outburst are nearly inversely proportional to the energy flux. P and h depend on the concentration and individual properties of the inclusions. In some cases they may tend to infinity. Then no outburst occurs and the sublimation rate monotonically decreases.

3. Solvable inclusions (frozen electrolytes). The aqueous solutions studied may be divided into three groups [7].

The first one is formed by frozen solutions of volatile substances, such as

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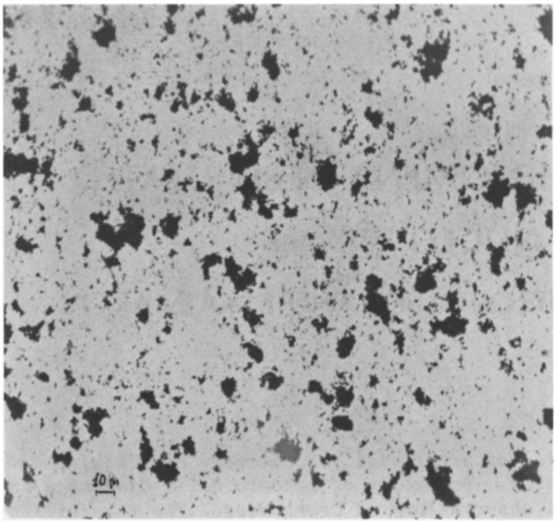

Figure 1. Conglomerates of 2 micron Ni particles. Initial concentration 0.35% (vol.).

NH_4OH, CH_3CN, etc. These solutions form matrices consisting of icy granules or do not form any matrices at all.

The second group consists of frozen solutions of compounds less volatile than water -- such as NaCl, $(NH_4)_2CO_3$ etc. During sublimation they form porous matrices. So, in this case meteoric matter may have to be formed directly on the cometary nucleus surface even when the main body of the nucleus is free of meteor particles, as B. J. Levin has suggested in 1962. Outbursts of such meteoric layers would supply the cometary atmosphere with clouds of dust. Peculiarities of this dust creating mechanism are studied now.

The third group is constituted by frozen solutions containing hydrated ions of Li, Mg and other strongly retaining water. These solutions form during sublimation very peculiar nonporous surface layers substantially hindering further sublimation.

Especially interesting is the problem of organic substances in comets.

A great number of experiments have shown, that the organic molecules of carbonic and amino-acids, aldegids, nitryls (examples see in Table I) - may be built up from a wide variety of possible combinations of simple compounds containing N, C, H, O under the action of any kind of energy sources (electrical discharge, heat, ultra-violet radiation, α, β, γ - rays). Such conditions could occur at early stages of comet formation and continue for very long times, as has been pointed out by many investigators and as has been manifested for instance by organic compounds of carbonaceous meteorites or organic molecules in space.

Therefore some frozen organic solutions were studied [2]. They turned out to belong mainly to the first or second group forming porous matrices and showing outbursts. Organic grains formed in such a way may exist sufficiently long and even contain optically active compounds. Stereoisomeres rotating the plane of polarization in opposite directions have a little different rate of evaporation and so the cometary atmosphere could gradually become enriched in stereoisomeres of one kind. In such a way the optical activity of comets suspected by some observers may be explained.

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TABLE I

EXAMPLES OF SOME SIMPLEST ORGANIC COMPOUNDS POSSIBLY PRESENT IN COMETARY NUCLEI

Compound	Formula	Molecular Weight
CARBONIC ACIDS		
Formic	H - COOH	46
Acetic	CH_3 - COOH	60
AMINO ACIDS		
Glycine	NH_2 - CH_2 - COOH	75
Alanine	CH_3 - $CH(NH_2)$ - COOH	89
Valine	$(CH_3)_2CH$ - $CH(NH_2)$ - COOH	117
Asparagic acid	HOOC - $CH(NH_2)$ - CH_2 - COOH	133
Glutaminic Acid	HOOC - $CH(NH_2)$ - $(CH_2)_2$ - COOH	147
NITRYLS		
Formonitryl	H - CN	27
Acetonitryl	CH_3 - CN	41
AMIDES		
Cyanamide	CN - NH_2	42
Formamide	HCO - NH_2	59
Carbamide	NH_2 - CO - NH_2	61

3.1 Example of the first group: H_2O + CH_3CN. Sublimation creates surface matrix of H_2O. The vapor pressure of CH_3CN breaks up the matrix and a cloud of icy powder is dragged away by the sublimating gases. This gives experimental

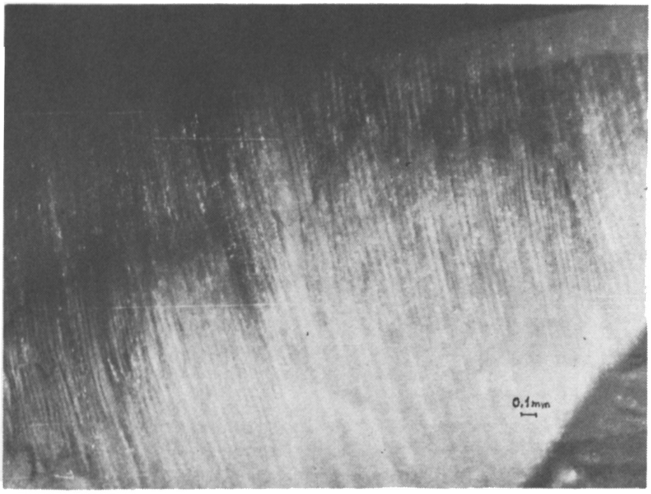

Figure 2a. Morphological peculiarities of an phenylalanine matrix. Low magnification. Initial concentration C = 3.10^{-3} M.

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confirmation of the predicted icy-grain halo in cometary atmospheres [4].

3.2 Examples of the second group. H_2O + amino acid, for instance phenylalanine [2]. The matrix is formed by phenylalanine and has a very interesting shape like a brush of long whiskers. Different phenylalanine matrices are represented on Figures 2a,b,c. They correspond to initial concentrations C in the range 10^{-2} M to 3.10^{-3} M, M being the normal concentration *i.e.*, one mole per litre. The matrix is brittle: it breaks easily into whisker fragments. Because of their diameters in the micron range light pressure is weak and these whisker fragments could form persistent meteor streams.

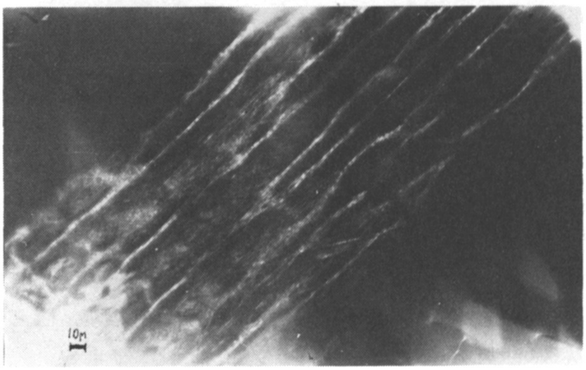

Figure 2b. Same as Fig. 2a. High magnification. $C = 10^{-2}$ M.

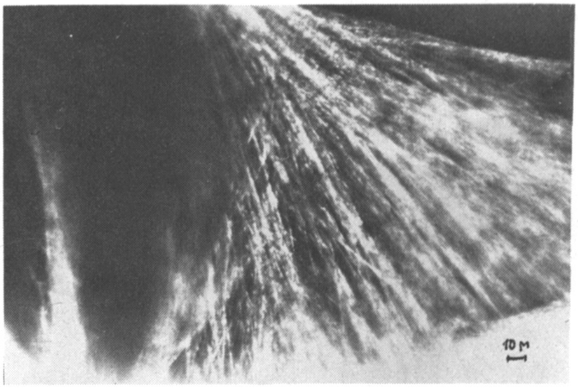

Figure 2c. Same as Fig. 2a. High magnification. $C = 3.10^{-3}$ M.

Another example: H_2O + carbamide. Carbamide forms the matrix. It is similar to the phenilalamine matrix. Fragments of it are represented on Figure 3. The initial concentration C = M.

Similar whiskers were observed when inorganic inclusions say NaCl of low concentration were involved as is shown on Figures 4a,b,c. Figures 4a and 4b correspond to C = M and 0.1 M. Fragments of NaCl matrices show no presence of whiskers. Figure 4c, corresponding to $C = 10^{-2}$ M shows long NaCl whisker fragments.

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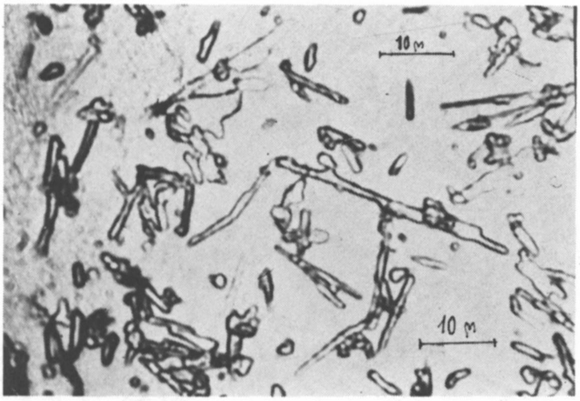

Figure 3. Carbamide matrix fragments.

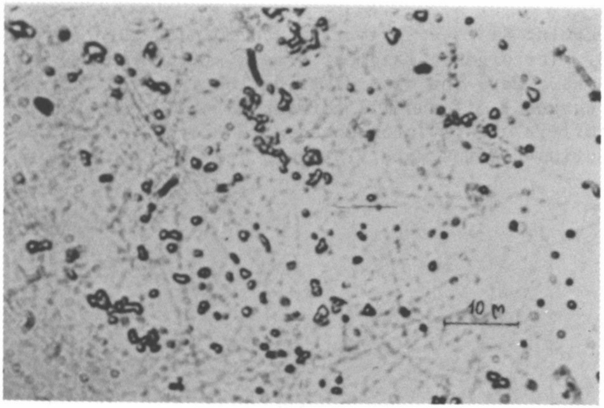

Figure 4a. NaCl matrix fragments. C = M.

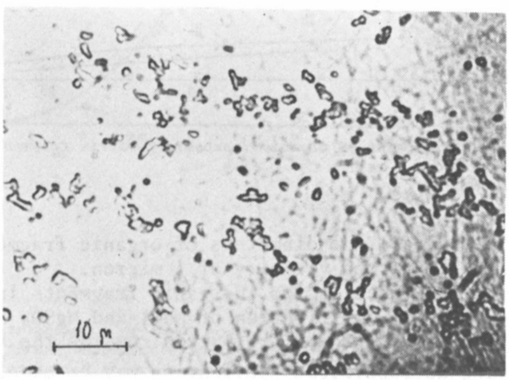

Figure 4b. Same as Fig. 4a. C = 0.1 M.

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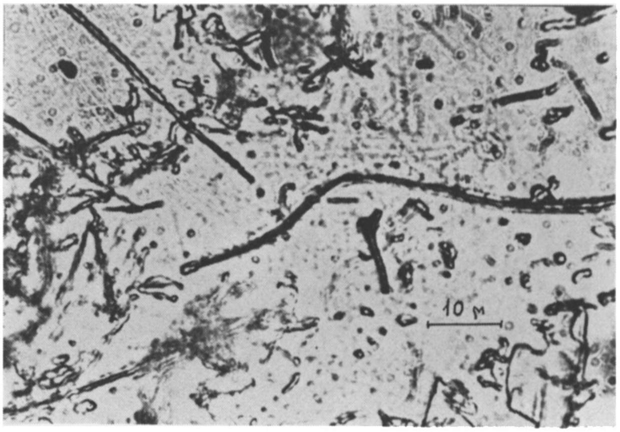

Figure 4c. Same as Fig. 4b. C = 0.01 M NaCl + 10^{-4} M NH_4OH.

3.3 The fragment sizes distribution was found separately for inorganic and organic matrices. The organic fragment size distribution is very sensitive to C as Figure 5 shows. Here the size distribution is given for carbamide matrices fragments. The curves I, II and III correspond to C equal M, 0.1 M, 0.01 M. At great C a cutoff is clearly pronounced at 6 micron length. At lower C the distribution function becomes more flattened and the cutoff is shifted to much greater length L.

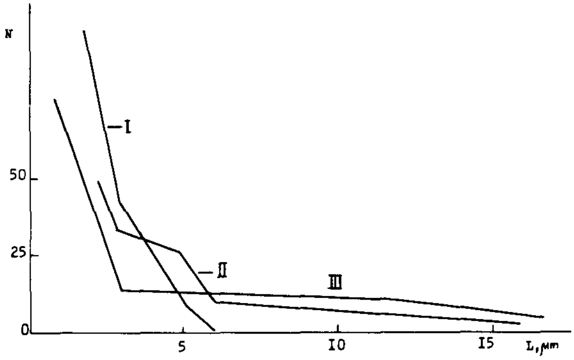

Figure 5. Size distribution of organic (carbamide) matrix fragments: I - C = M; II - C = 0.1 M; III - C = 0.01 M.

It is remarkable that all the diameters of organic fragments have the same order of magnitude and lie in the vicinity of 1 micron.

The size distribution function for inorganic fragments is less dependent on C. As an example the size distribution of NaCl and $MgSO_4$ at C = M is given on Figure 6. Down to C = 0.1 M the distribution remains the same.

4. An interesting astrophysical application may be made. The presence of elongated meteor particles should facilitate the observation of negative polar-

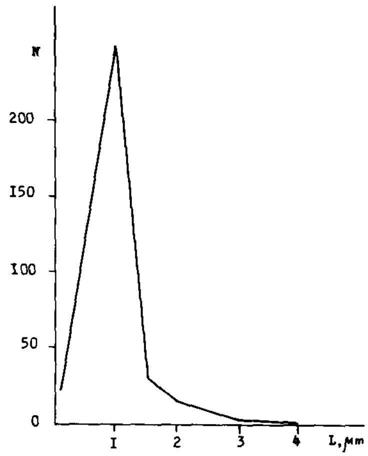

Figure 6. *Size distribution of inorganic (NaCl) matrix fragments. C = M. At C = 0.1 M the distribution is essentially the same. At C = 0.01 M elongated fragments appear.*

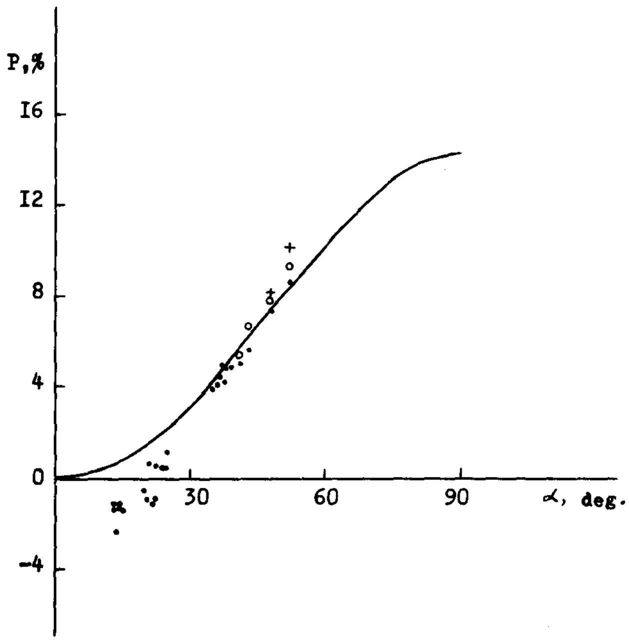

Figure 7. *Polarization p of comet West as a function of phase angle α. Dots of different shape correspond to different diaphragm diameters. Negative polarization at small α is clearly pronounced. The curve represents Ohman's relation usually adopted for comets. After N. N. Kiselev and G. P. Chernova.*

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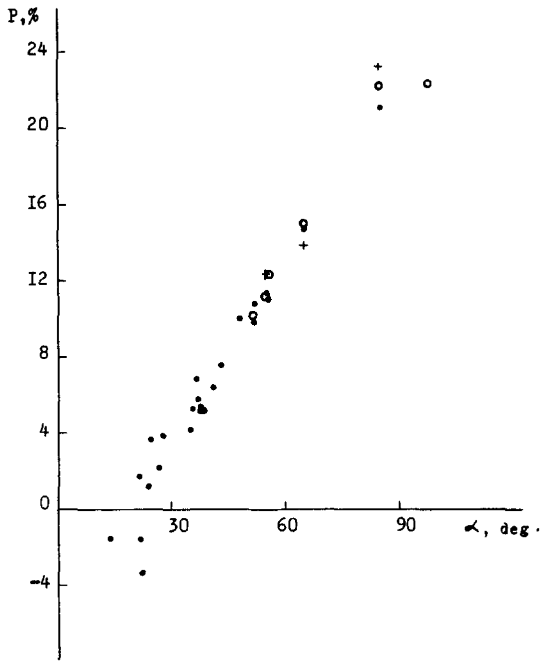

Figure 8. Same as Fig. 7 for a narrow Δλ = 50 Å region in the continuum at λ = 5300 Å.

ization in cometary heads. The first attempt to discover such a polarization was undertaken by N. N. Kiselev and G. P. Chernova at Dushanbe [8]. For this purpose comet West was observed in a wide range of phase angles α. Figure 7 shows their results. The curve corresponds to the formula:

$$P_\alpha = P_{90} \sin^2\alpha / (1 + P_{90} \cos^2\alpha)$$

used usually to represent polarizational observations. The dots of different shape represent the observed percent of polarization in the visual region (V - region of Johnson and Morgan) with different diaphragms. The negative polarization at small α (or great scattering angles) is clearly established. The same results were obtained for a narrow (Δλ = 50 Å) region in the continuum at λ = 5300 Å (Figure 8).

5. The details of amino acid matrices formation may be of cosmochemical interest. It seems, that amino acid molecules liberated during sublimation of ice are drifting on the sublimating surface. The surface diffusion coefficient D for them at T ≈ 237 K was measured by us and turned to be near the diffusion rate in liquids namely 3.6×10^{-2} cm^2 sec^{-1} for carbamide, 8.9×10^{-3} cm^2 sec^{-1} for glycine and so on. So the molecules have time enough to gather (preferably at dislocations) to orient themselves and to enter into combination. The energy for chemical bounding is supplied by a beam of ultraviolet light. Peculiar semiconductor properties of the icy surface also stimulate chemical reactions giving a clearly pronounced catalytic effect. The whiskers built in such a way called by us sublicones are of an interesting shape resembling a pencil without

the inner pivot. The biuretic reaction shows the presence of peptide bounds in such sublicones. Aren't we facing the creation of a new effective method of biochemical synthesis?

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DISCUSSION

ARNOLD: Two points: 1. I also wish to encourage astronomical observations to test the presence or absence of long whiskers or chains of particles in comet dust tails or other dusty places. 2. Since impurities such as inorganic salts or organic molecules are not soluble in ice (solid H_2O), I have the impression that for such substances the impurities will form solids at the time of freezing, not later during your experiments.

DOBROVOLSKY: At not too high concentrations many substances form clathrates which have physical properties almost the same, as pure water ice has. It seems to me that that was the case in our experiments with frozen electrolites of low concentrations.

COSMOVICI: I do not really understand the experimental procedure. At which T and P do you carry out your experiments?

DOBROVOLSKY: Most experiments were performed at pressures 10^{-5} - 10^{-6} mm Hg. T varied in the range 180 - 240^{o} K, corresponding to different solar distances.

KELLER: How would the absence of gravity influence your experimental results?

DOBROVOLSKY: Not substantially. I think the gravity influence is of minor importance. To avoid gravitational destruction of sublimating nuclei, the container opening was never oriented downward.

SMOLUCHOWSKI: Structure of ice depends very much on temperature of formation, whether it is condensed from vapor or frozen water. I wonder to what extent your ice was normal hexagonal and whether impurities would not enhance the formation of amorphous ices and alter their stability.

DOBROVOLSKY: In the experiments reported, the ices were built of frozen water. Their structure depended on the concentration and nature of admixtures and on the freezing conditions.

*BRANDT: The icy grain halos (IGH) of Comet Kohoutek (*Ap.J., 201*, 749, 1975)* *and Comet West (Hobbs, Brandt, and Maran, 1976) have been detected through continuum radio observations at 3.71 cm with the NRAO interferometer. The properties are consistent with Delsemme's predictions with an enhanced density. The day of our detection for comet West corresponded to one of the days of nuclear splitting; observations the day before showed no IGH.*

WHIPPLE: I can testify to the escape of solid particles from ice in a vacuum under simulated solar radiation, having seen the experiment in Leningrad in 1970. The velocities were several meters per second.

DOBROVOLSKY: I would be happy to welcome you next time at both the laboratories at Leningrad and at Dushanbe.