55. A NONGRAVITATIONAL EFFECT IN THE SIMULATION OF COMETARY PHENOMENA

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Abstract. Experimental results for the determination of the exhaust thrust developed by vacuum-sublimation products of H_2O ice and frozen aqueous electrolytes are described. The contribution of the exhaust thrust to nongravitational effects on comets is discussed.

1. Introduction

Comets are characterized by extremely violent processes (Dobrovol'skij, 1961). Modern studies of these processes involve the use of both the methods of classical optics and methods based on the latest advances in experimental techniques (Potter and del Duca, 1964; Danielsson and Kasai, 1968).

This paper deals with experiments for determining the exhaust thrust resulting from the sublimation of various types of ice in a laboratory simulation of cometary phenomena under conditions closely approximating those of outer space.

The particular interest in this problem is that when a comet passes near the Sun its orbital parameters tend to deviate from the values calculated purely from consideration of the gravitational attractions of the Sun and planets. For comets with small perihelion distances this deviation is the rule rather than the exception.

It is a reasonable assumption that such anomalies may be due to the comet's reaction to ejected mass. This hypothesis was first advanced by Bessel as long ago as 1836. It was further developed by Dubyago (1948), Whipple (1950), and Makover (1955, 1956).

Sekanina (1967) gave a theoretical treatment of the 'impulse' effect hypothesis, which assumes a local explosive process in a cometary nucleus of arbitrary shape, resulting in the ejection of fairly substantial amounts of material. The ejection manifests itself as an impulse noticeably affecting the motion of the nucleus.

Ejections from real comets have both solid-particle and gaseous components, and the complete phenomenon is rather complicated. Therefore, the first stage in our investigation of these processes was to study the pressure developed by ice sublimation products under conditions of high vacuum and low temperature that are similar to those in outer space.

2. Experimental Techniques

The experiment was carried out in the laboratory using a specially designed glass vacuum chamber cooled by liquid air and a torsion balance set up inside the chamber. The balance carried cells containing ice samples mounted so that the torque produced by the sublimating ice could be registered using a system of mirrors.

The cells were fitted with a miniature heating element and a copper-constantan

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thermocouple. The heater and thermocouple leads were thin (0.05 and 0.1 mm) wires, so that the balance torsion would be scarcely affected. The balance was calibrated by means of an air jet of known pressure. Its constant was found to be 4.4 divisions per milligram, and the calibration was checked from experiment to experiment.

The test samples of ice were prepared outside the vacuum chamber. The cells were placed inside and the evacuation began. After a while the bottom section of the chamber was cooled with liquid air. A certain delay in cooling occurred because the evacuation was accompanied by removal from the cell walls of frost that had settled there during the preparation of the ice samples and which produced undesirable effects upon the balance readings when sublimating.

Cooling of the chamber brought the temperature of the sample to −135 or −140 °C. The position of the balance index at this temperature was taken as the reference point, because the thrust was then far below the sensitivity range of the balance.

After cooling the samples and generating a sufficiently high vacuum (10^{-5} to 10^{-6} T) the heating elements were switched on and a certain amount of heat input was supplied to the ice; this was maintained at a constant level during the experimental run.

The power input W could be calculated from the formula

$$W = UI, \tag{1}$$

where U is the voltage and I the current, but this was not precisely the amount of power consumed in heating and sublimating the ice. As a matter of fact, the heat energy W applied to the test sample cell is expended in several ways: on the sublimation product (W_{subl}), residual gas molecules (W_{gas}), via the thermocouple and heater leads (W_{therm}) and by radiation (W_{rad}):

$$W = W_{\mathrm{subl}} + W_{\mathrm{gas}} + W_{\mathrm{therm}} + W_{\mathrm{rad}}. \tag{2}$$

The last three terms introduce an element of uncertainty into the evaluation of the sublimation energy. Calculation of the appropriate heat flows is a fairly complicated problem, and the following method was used instead (Kajmakov and Sharkov, 1969). The cells were filled with fine-grain silica sand, packed by means of a glass filter. The balance and cells were then cooled down and power supplied to the heaters, just as when the cells contained ice. The steady-state temperature of the cell (without ice) was measured as a function of the power input:

$$T^{\mathrm{cell}}_{s-s} = f_1(W'), \tag{3}$$

where $W' = W'_{\mathrm{gas}} + W'_{\mathrm{therm}} + W'_{\mathrm{rad}}$. Radiation losses are insignificant, and hence the difference between W_{rad} and W'_{rad} is negligible. It was also shown experimentally that W'_{gas} differs but slightly from W_{gas}. In experimental runs using ice samples, values of the steady-state temperature were obtained for various power input levels, giving

$$T^{\mathrm{cell+ice}}_{s-s} = f_2(W). \tag{4}$$

Using Equations (3) and (4), it is possible to plot a graph of 'equilibrium' ice temperatures

$$T^{\mathrm{ice}}_{s-s} = f_3(W) \tag{5}$$

for the case where all the energy input is spent entirely on molecular sublimation, i.e., on breaking the bonds between sublimating molecules and on their kinetic energy. By this method we were able to allow for the effect of specific conditions upon the experimental results.

The power-input calibration of the cells proved to be different for the two types of cell used. This caused further complications: during ice-sublimation runs it was found necessary to apply to the cells different amounts of power to maintain W_{subl} constant, or in thrust calculations to determine the contribution of each cell to the overall impulse recorded by the torsion balance. The method could be utilized if we made use of the relation between the flow of the sublimating molecules and W_{subl} (Kajmakov and Sharkov, 1969).

After establishing the equilibrium temperature for a given power input we measured the exhaust thrust. The time required for stabilizing the temperature, and hence the exhaust thrust, was mainly dependent upon the absolute temperature of the ice. If the power input were low, an experimental run could last as long as 10 to 12 h.

We have also conducted experiments using frozen aqueous electrolyte solutions (Kajmakov and Sharkov, 1972). Special attention was given to preparing these samples. High purity chemicals were used, and in order to avoid variations in concentration in different parts of the cell during freezing (salting out) the ice samples were prepared by freezing one layer at a time.

3. Measurements and Discussion

Using the techniques described above, we measured the exhaust thrust $\bar{p}$ developed by sublimating H_2O molecules from unit surface area for various specific power inputs to the ice. The thrust varied from (0.10 ± 0.01) to (4.0 ± 0.4) mg cm^{-2} over a power input range of 0.016 to 0.29 W cm^{-2}, and this corresponds to a temperature range of -75 to -50 °C.

It will be seen from Figure 1 that the experimental relationship between thrust and temperature is generally in good agreement with theory. The theoretical thrust may be calculated from

$$\bar{p} = JV_x, \tag{6}$$

where J is the ice consumption and V_x is the mean molecular velocity in a given direction. The ice consumption is given by the familiar equation of the kinetic theory of gases:

$$J = \alpha p \sqrt{(M/2\pi RT)}, \tag{7}$$

where p is the saturated vapour pressure at the temperature T, M is the total molecular weight of the substance, R the gas constant, and α the Langmuir factor (allowing for the return and partial condensation of the sublimating molecules). The velocity V_x is given by

$$V_x = \sqrt{(kT/2\pi m)} \tag{8}$$

(Epifanov, 1965), where k is the Boltzmann constant and m the molecular weight. Since $R = kN$ and $M = mN$ (N being Avogadro's number), it follows that

$$\bar{p} = \alpha p / 2\pi. \tag{9}$$

The factor α is assumed to be unity. This is justifiable, since at a pressure of the order 10^{-6} T and at low temperatures the free path of the sublimating molecules was twice the size of the sample.

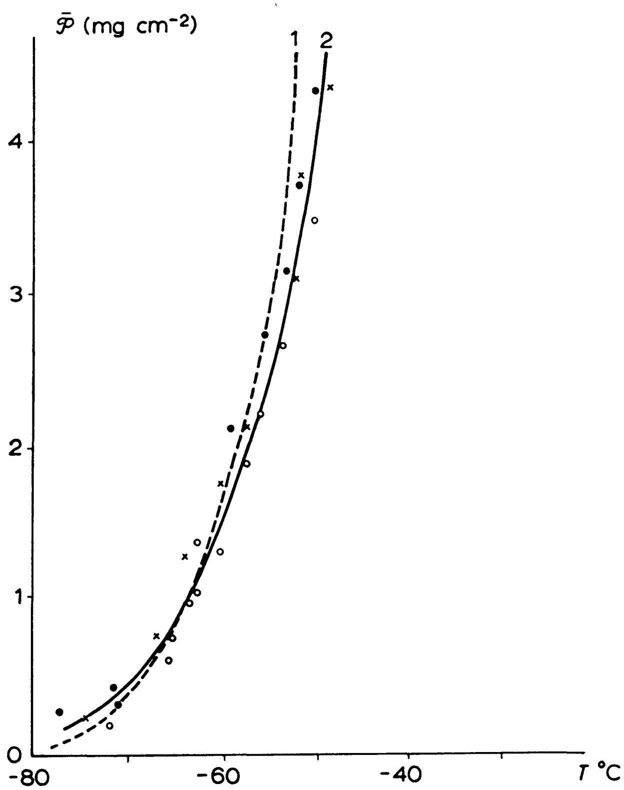

Fig. 1. Exhaust thrust $\bar{p}$ (mg cm^{-2}) due to H_2O ice sublimation versus ice surface temperature T (°C). The broken curve (labelled 1) is theoretical, the solid curve (labelled 2) experimental.

In the upper part of the figure there is some deviation between the experimental and theoretical curves. This is because direct measurements of surface temperature involve considerable experimental difficulties, and the surface temperature was therefore estimated from temperature gradients measured for various power inputs.

In subsequent experiments the power and temperature ranges were expanded, and thrust relationships were obtained for temperatures -33 to -75 °C over a specific power input range of 0.016 to 0.46 W cm^{-2}. Above -50 °C (0.30 W cm^{-2}) the experimental curve deviates strongly from the theoretical one (see Figure 2) because of the 'greenhouse effect'. At high power inputs the quantity of molecules leaving the surface of the sublimating ice is so great that some of them collide and return to the surface. A blanket of H_2O vapour is formed over the surface; this hinders the sublimation products and causes a decrease in the thrust. As the temperature increases further there is a reduction in the rate of increase of thrust.

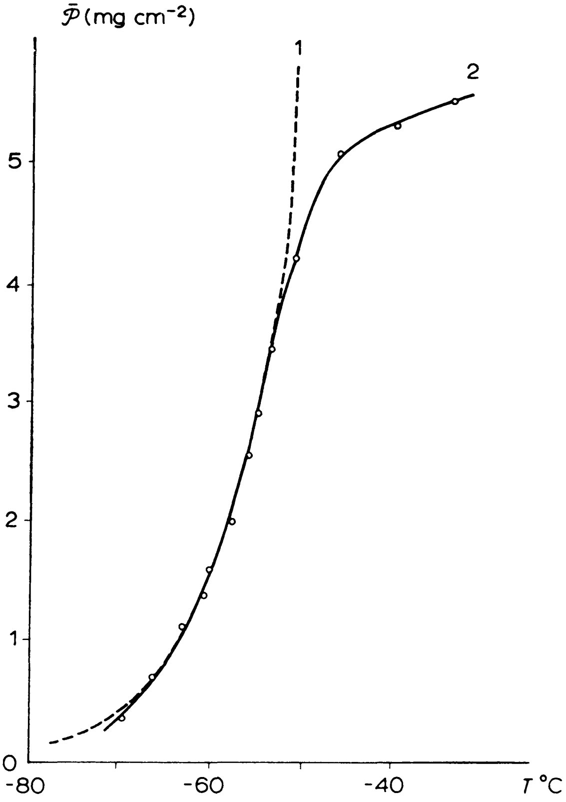

Fig. 2. The greenhouse effect. See Figure 1.

There is a further difference between the curves at the lower end. This occurred at the termination of the experimental runs, the experimental curve being plotted as the temperature decreased. The difference may be explained as follows: when the ice surface drops down the cell, the cell walls begin to act as guides for the molecular outflow, and this leads to an increased thrust.

The theoretical curve was calculated on the assumption that there was an equally probable distribution of molecules at all outflow angles. Good correlation between experiment and theory bears out this assumption, showing that the sublimation products leave the surface in conformity with the cosine law. Earlier attempts at experimental confirmation of this, by other methods, had failed to give an unequivocal answer.

In ices prepared from 1.5N KCl solution, the temperature tended to rise as the water content decreased. This was due to the formation of a friable salt crust (matrix) over the ice surface. The temperature rise produces a certain 'pressure head' of sublimation products, and this in turn ensures a flow of sublimating molecules through the matrix pores, equivalent to the power input. Since the structure of the matrix varies with power input, the latter was maintained constant throughout the experiment.

As power is applied to the ice, there is a steep rise in thrust up to a certain level. Sublimation of H_2O molecules is then being effected through a very thin matrix layer that has formed in the process of evacuating and cooling the system, and the exhaust thrust tends therefore to reach the value for pure H_2O ice at the same power input. The shorter the time for evacuation and cooling, the closer the two values are. Subsequently, as the matrix increases in thickness, the thrust magnitude falls off slowly. It falls off more and more slowly until it practically reaches a plateau. The variation in thrust with time is illustrated in Figure 3 for two values of the power input.

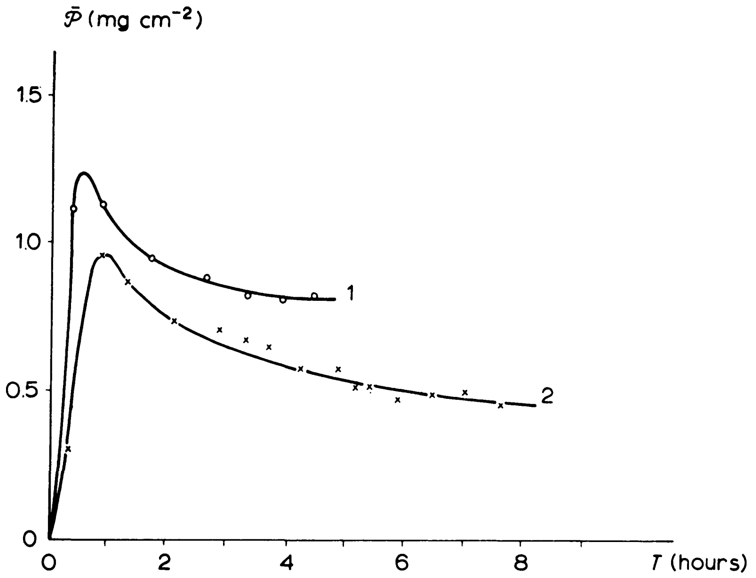

Fig. 3. Exhaust thrust $\bar{p}$ (mg cm^{-2}) versus time t (hours) for frozen aqueous KCl solution at specific power inputs (1) 0.064 W cm^{-2}; (2) 0.058 W cm^{-2}.

Since the measurements conducted on the flow of sublimating material from KCl ice have shown them to be equivalent to flow from pure H_2O ice at identical power inputs, the fall-off in exhaust thrust with time and the difference generally from the thrust developed by H_2O ice can only be attributed to changes in the outflow velocity of the molecules.

If we assume that the plateau describes the thrust at a given power input, the estimated decrease in velocity due to the passage of the sublimating molecules through a dust-matrix layer 8 to 10 mm thick would be by a factor of 2 to 3.

Experiments were also conducted on 1.5N LiCl solution. Li^+ ions actively attract water to form a hydrate deposit (Konstantinov and Troshin, 1966), and it is interesting to compare the behaviour of matrix-forming substances having different types of ions.

Figure 4 shows that the thrust developed by sublimating molecules in frozen LiCl solution is lower than in the case of pure H_2O ice, although it is higher than for frozen KCl solution. In addition, it was found in the course of the experiments with LiCl solution that the increase in thrust did not occur immediately upon application of power but after a lapse of about 2 h. It may be assumed that a surface layer of low permeability is formed on the ice, unlike the salt matrix of frozen solutions of the KCl type. This crust is so dense that the thrust developed is below the sensitivity limit of the balance. The crust is then thrown off by internal pressure and a rise in thrust follows.

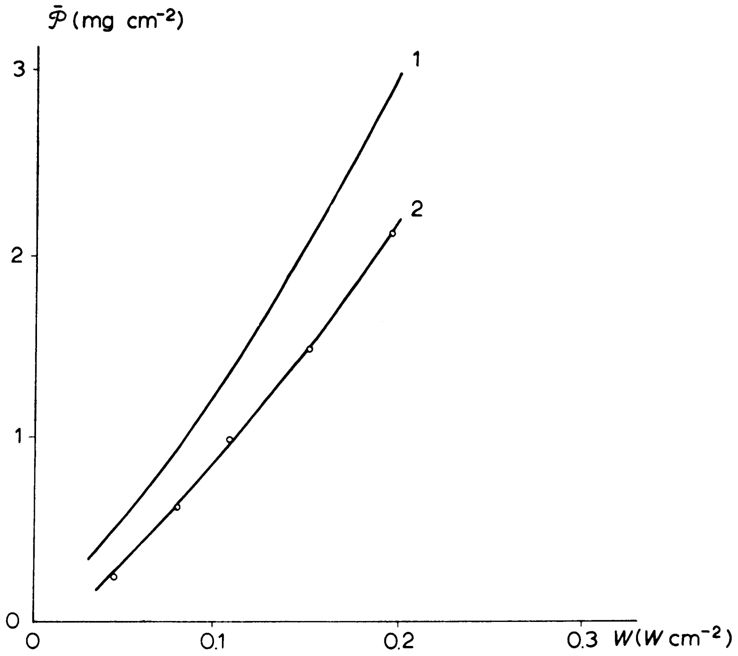

Fig. 4. Exhaust thrust $\bar{p}$ (mg cm^{-2}) versus power input W (W cm^{-2}) for (1) H_2O ice; (2) frozen aqueous LiCl solution.

It is possible that at lower power inputs the conditions for formation and growth of a matrix crust would be more favourable and the behaviour of LiCl ice similar to that of KCl ice.

4. Conclusions

The following conclusions can be drawn from the experiments and processing of the experimental data:

(1) Within the temperature range −75 to −50 °C, the exhaust thrust varies from (0.10 ± 0.01) to (4.0 ± 0.4) mg cm^{-2}.

(2) These values for the exhaust thrust clearly indicate that ice sublimation products are discharged at all angles (according to the cosine law).

(3) At temperatures above −50 °C, the exhaust thrust was observed to deviate sharply from theory owing to the greenhouse effect associated with the formation of a blanket of gas near the sublimating ice surface.

(4) A porous matrix on the sublimating ice surface leads to a reduction in the exhaust thrust as a result of a decrease in the velocities of the sublimating molecules.

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