MODEL OF ELEMENTARY STEP ON THE BASAL FACE OF AN ICE CRYSTAL

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1. INTRODUCTION

It is notorious that in dependence on temperature and supersaturation of the environment we observe variations of ice-crystal shapes growing from water vapour. It may be said that as a result of a number of laboratory studies (see, e.g. [1–5]) as well as of direct observations in the atmosphere**) we now dispose of a fairly complete picture of this dependence (Figs 1, 2 in [5]). Essentially, we discern two types of variations of ice crystal habit. On the one hand, there are changes characterized by the transition of the c : a axes ratio from values lower than unity to values larger than unity, or vice versa, which may be regarded as fundamental changes. On the other hand, in the course of growth we witness changes in secondary growth features (transition from simple plates to sector plates or dendrites, from solid prisms to hollow prisms, etc.), which may be characterized as secondary changes. Such a division is, however, formal in as much as both types of changes often occur simultaneously and mutually affect each other. An inquiry into the causes of these changes, and more particularly into the causes of quantitative changes is more involved. It is obvious that the basic factor influencing the ice-crystal habit is temperature: temperature changes result primarily in elementary transformations. Distinct changes occur at -4, -10 and about -22°C (plates-prisms-plates-prisms); recent observations of the growth of ice crystals at lower temperatures (down to -90°C [3]) could not add any substantial information to this sequence. Supersaturation does not affect the elementary shape of the crystals, but exerts a substantial influence on the rate of growth, and the related growth features.

All these observations make for the conclusion that the causes of the changes in the shape of crystals growing from water vapour must be sought, in the first place, in the thermal sensitivity of the phenomena developing on the crystal surface, whereas the diffusion field about the crystal only attenuates, or potentiates, the prevailing growth of the crystal in one or another direction.

In keeping with this inference, experimental work performed recently has proved, in particular, the importance of the surface diffusion in forming the shape of the crystal [8]. The motion of steps on the basal face of ice was studied, and from changes in the rate of the steps depending upon temperature, conclusions concerning thermal changes of the habit were drawn. However, an overall elucidation of the dependence of the shape on external conditions would require experimental results regarding the prism face. In view of this situation, it would be of great importance to construct a theoretical model of the growth step which would permit an application to the basal and the prismatic surfaces.

Hobbs and Scott [9] attempted to proceed with a theoretical inquiry into the growth of a step on the basal surface. Their unidirectional model does not permit a direct application to the prism face. However, since these investigators, who based their work on experimental values and built them into the model, have obtained values of a correct order, we shall make references to their work. We shall construct a model of a growth of steps on the basal face, assuming a lattice of ice, analogous to the lattice of wurtzite. We shall confine our inquiry to the steps of the smallest heights, an analogy of monomolecular steps in close-packed lattices.

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**) A survey of older works describing direct observations of the atmosphere is given in [13]; in recent years systematic observations are carried out, e.g., in Japan.

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2. FORMULATION OF THE TASK

Let us term the elementary step on the basal face an uncompleted layer, composed of two molecular planes, and let us inquire into the growth of the elementary step of the mean direction $[2110]$, (i.e. the most closely packed orientation) as a result of addition of particles coming from the adsorbed layer, as well as directly from the atmosphere surrounding the crystal (Fig. 1a, b). The formulation of our task shall be based upon the model of the phenomena coming into play during the growth of the crystal, which is analogous to the Gevers model [12].

All the particles which will reach the step either directly from the environment of the crystal, or from the adsorbed layer, migrate along the step to kink sites, where they may be built in. Let us assume that all the particles which have reached a kink site shall be removed instantly and transferred back into vapour, outside the diffusion boundary layer surrounding the crystal. This process results in a stationary flux of particles to kink sites, the magnitude of this flux, which at a given temperature is a function of the supersaturation, being a measure of the rate of motion of the step. There is, however, a certain probability that the particle, which has reached the kink site, will once more evaporate either on to the surface or directly into the environment of the crystal. The number of particles which evaporate from the kink site per unit time depends on temperature, and in the case of dynamical equilibrium of the crystal with its environment it will correspond with the number of particles which are built into the kink site, i.e. hypothetically removed. As a consequence, for the resultant flux of particles, at the sacrifice of which the crystal will grow, we may write:

\[ q = q^* - q_0^* , \]

where $q^*$ is the hypothetical flow of particles described above, and $q_0^*$ is the value of this flow in the case of a dynamical equilibrium at the given temperature. The magnitude of the rate of the motion of a step of elementary height can then be described formally by expression

\[ v = Kq , \]

where $K$ is the geometrical factor ($[K] = \text{cm}^2$).