# The Shape and Riming Properties of Ice Crystals in Natural Clouds

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ABSTRACT

Individual ice crystals have been collected and replicated. The effect of the falling motion is found to enhance the growth along the "*c*" axis of columns and the dendritic growth of plane ice crystals. It is found that the onset of riming of ice crystals is controlled by crystal size; for columnar crystals the most sensitive parameter is the length along the "*a*" axis, while for plane crystals it is the diameter. Freely-falling ice crystals are oriented so as to present the maximum resistance to motion.

Some consideration is also given to the collection efficiency of columnar ice crystals for cloud droplets.

## 1. Introduction

The study of ice crystals collected in natural clouds was pioneered many years ago by Weickmann (1947), but this field has only enjoyed widespread attention in the past few years.

The relationship between the shape of natural ice crystals and the temperature at which they have grown is well established and agrees with the results of laboratory experiments [see, for example, Mason (1957) and Magono and Lee (1966)]. Within each category of crystal shape there is a wide variation in the ratio of dimensions along the crystal axes. These dimensions are studied in the present work using crystals sampled in natural clouds. Various changes in shape from plate to dendrite and from column to long column illustrate the effect of ventilation on the growth mode of the falling crystal.

The concentration of ice crystals in natural clouds has been studied in the last few years, and it has become clear that numbers far in excess of the concentration of ice nuclei are generated in some clouds. Recent work in this field is summarized by Mossop and Ono (1969). This apparent multiplication of ice crystals may be associated with the process of riming of the crystals. As long ago as 1940 it was reported by Findeisen that ice splinters were thrown off when supercooled water drops impinged on an ice-covered test body. Thus, the riming process is of great interest for this reason, in addition to its fundamental importance in the growth of ice particles.

So far, few studies have been made of the riming of natural ice crystals. Nakaya (1954) measured the sizes of the frozen droplets attached to ice crystals. Kuroiwa (1955) calculated the amount of evaporation of droplets moving uniformly relative to ice spheres of 30–100 $\mu$ in diameter and showed that droplets $\gtrsim 1$–$2\ \mu$ in diameter could reach the ice sphere without complete evaporation. Todd (1964) has made numerical calculations on the onset of riming, assuming that there is a similarity between the collection efficiency of ice crystals and of water drops.

In the present paper we report observations of the minimum dimensions of crystal necessary for riming to be possible, and also of the sizes of the collected droplets.

The riming of ice crystals also provides evidence of the orientation in which the crystals fell. Previously, the orientation of falling ice crystals has been studied by laboratory experiments on models. Field observations by Magono (1953), using a stroboscopic method, showed that the plate-type snow crystal falls with its main plane horizontal. We present further evidence based upon the riming of ice crystals collected both on the ground and from an aircraft.

## 2. Source of material

Cloud sampling was carried out during the winters of 1966 and 1967 in southeast Australia using an instrumented aircraft. The techniques of replicating ice crystals and some of the results are described by Mossop *et al.* (1967), Mossop (1968), and Mossop and Ono (1969).

The present study made use of ice crystal replicas obtained by exposing glass-slides coated with a 1% solution of formvar in ethylene dichloride, in a "decelerator" tube fixed to the aircraft fuselage. In this device cloud particles were slowed down so that when they struck the collecting surface their speed relative to the aircraft was much less than the original 90–100 kt. In this way breakage of ice crystals was reduced, though not entirely eliminated.

Eleven cases were selected in which ice crystals and water drops were simultaneously sampled. One could then reasonably assume that the crystals were growing at water saturation.

TABLE 1. Details of sampling penetrations of clouds.

| Date | Cloud type | Cloud top Height (km) | Cloud top Temperature (°C) | Sampling level Pass | Sampling level Height (km) | Sampling level Temperature (°C) | Particles sampled | Types of ice crystals |
|---|---|---|---|---|---|---|---|---|
| 10 August 1966 | Stratocumulus | 2.9 | −6 | A | 2.3 | −2 | Ice & water | Columnar |
| 11 August 1966 | Stratus | 5.8 | −33 | A | 5.6 | −32 | Ice | Columnar & plane |
| | Cumulus | 3.9 | −15 | B | 3.9 | −15 | Ice & water | Columnar & plane |
| 22 August 1966 | Cumulus | 5.2 | −25 | A | 4.3 | −21 | Ice & water | Columnar & plane |
| | Cumulus | 4.3 | −21 | B | 3.3 | −15 | Ice & water | Columnar & plane |
| 13 October 1966 | Cumulus | 5.8 | −20 | A | 5.2 | −15 | Ice & water | Columnar & plane |
| 15 October 1966 | Altostratus | 5.8 | −18 | A | 5.6 | −17 | Ice & water | Columnar & plane |
| | Altocumulus | 5.6 | −16 | B | 5.2 | −15 | Ice & water | Columnar & plane |
| 18 October 1966 | Cumulonimbus | >5.5 | <−20 | B | 5.2 | −17 | Ice & water | Columnar & plane |
| | Cumulonimbus | >5.5 | <−20 | C | 4.7 | −13 | Ice, water & graupel | Columnar & plane |
| 22 July 1967 | Cumulus | 3.6 | −5 | | 2.9 | −2 | Ice & water | Columnar |
| 1 August 1967 | Stratus | 2.5 | −7 | | 2.3 | −5 | Chiefly water | Columnar |

In Table 1 we give a brief summary of the characteristics of the clouds studied. Further details are given in the publications cited above.

The discussion of orientation of falling ice crystals is based upon photographs of crystals collected both from an aircraft and on the ground at Sugadaira, Japan, in 1964.

## 3. The growth mode of ice crystals in clouds

The forms in which ice crystals grow have been chiefly studied in laboratory experiments where the environment was almost at rest. However, as pointed out by Mason (1953), Isono (1959), and recently by Hallett (1965), as soon as natural ice crystals grow large enough to have an appreciable fall speed, their mode of growth is influenced by ventilation. The diffusion field around them will be disturbed from its equilibrium pattern and will be limited to a boundary layer around the ice crystal. The concentration and temperature gradients will be greatest where this boundary layer is thinnest; namely, at the edges of falling plates and at the ends of falling columns. Ventilation will therefore encourage the supersatura-

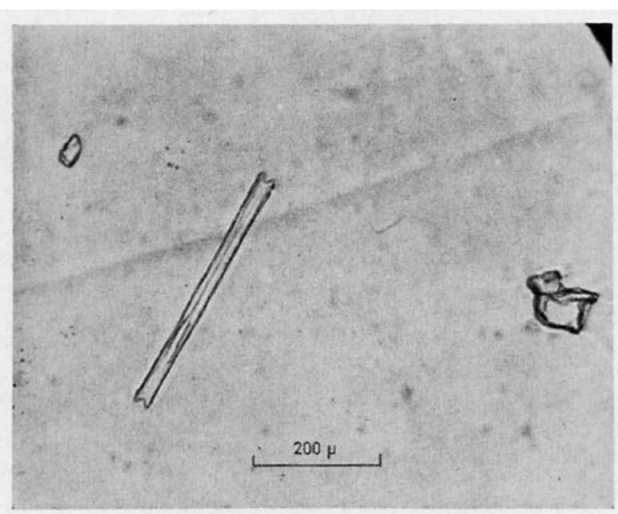


FIG. 1. Sheath ice crystal observed at −5C, 1 August 1967.

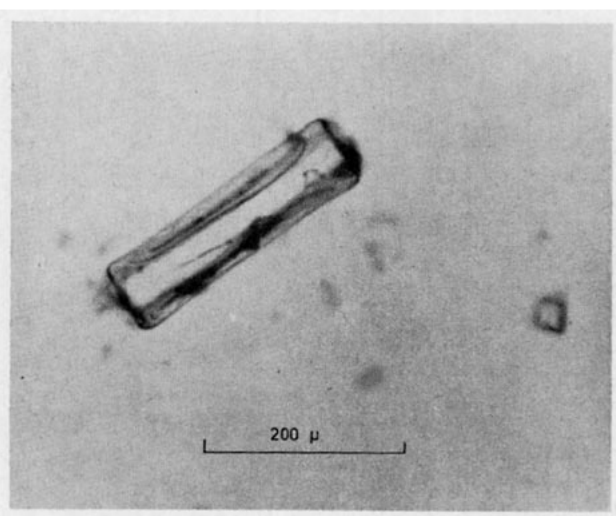


FIG. 2. Warm-region column observed at −2C, 10 August 1966.

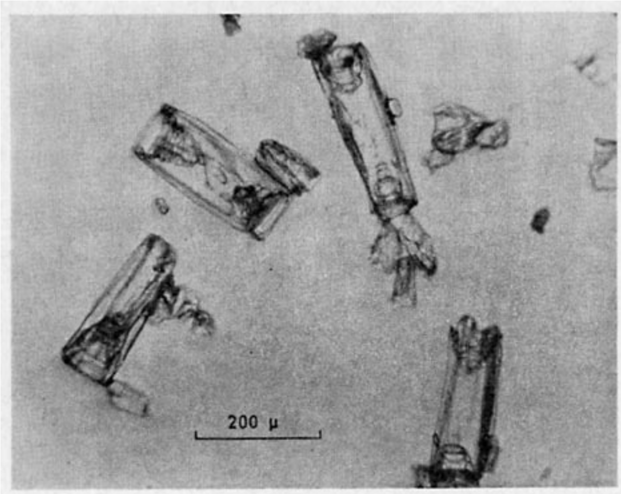


FIG. 3. Cold-region column observed at −32C, 11 August 1966.

tion-dependent transition from plate to dendrite and from column to long column.

*a. Columnar ice crystals*

The columnar ice crystals were classified into four groups as follows:

1) Sheath crystals observed on 22 July 1967 (cloud top temperature −5C, sampling temperature −2C) and on 1 August 1967 (cloud top −7C, sampled at −5C) (see Fig. 1).

2) Warm-region columns observed on 10 August 1966 (cloud top −6C, sampled at −2C) and 22 July 1967 (cloud top −5C, sampled at −2C) (see Fig. 2).

3) Cold-region columns observed on 11 August 1966 (cloud top −33C, sampled at −32C) (see Fig. 3).

4) Columns with end plates observed on 22 August 1966 (cloud top −21C, sampled at −15C) and 13 October 1966 at −15C (cloud top −20C, sampled at −15C) (see Fig. 4).

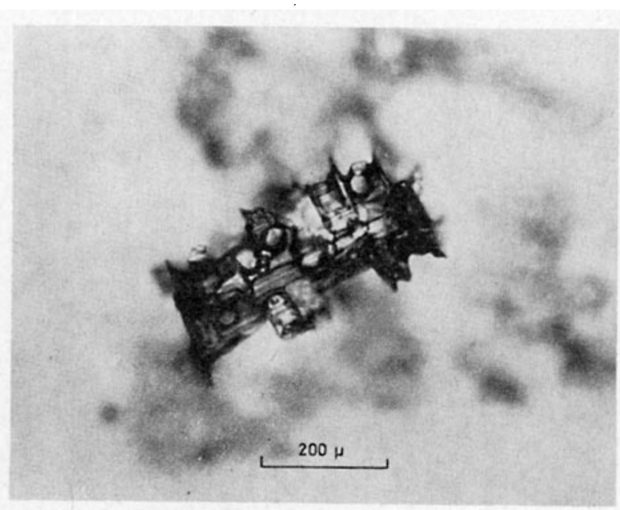


FIG. 4. Column with end plates observed at −15C, 22 August 1966. Accreted cloud droplets froze with the same "*c*" axis orientation as that of the substrate column crystal.

The relation between the length along the major axis and that along the minor axis of columnar crystals is shown in Fig. 5.

It is apparent that the various groups of ice crystals fall into characteristic regions of this diagram and full lines have been used to mark the boundaries between the regions.

The length of the minor axis of sheath crystals does not exceed 50 μ, while the major axis can be as long as 500 μ. It is apparent that growth along the major axis can continue while that along the minor axis virtually ceases as a length of 50 μ is approached. The full line for sheath crystals agrees with the maximum growth curve obtained by Isono *et al.* (1956) after seeding a supercooled fog at −4.4C. The figures on the line are the growth time in minutes obtained by them.

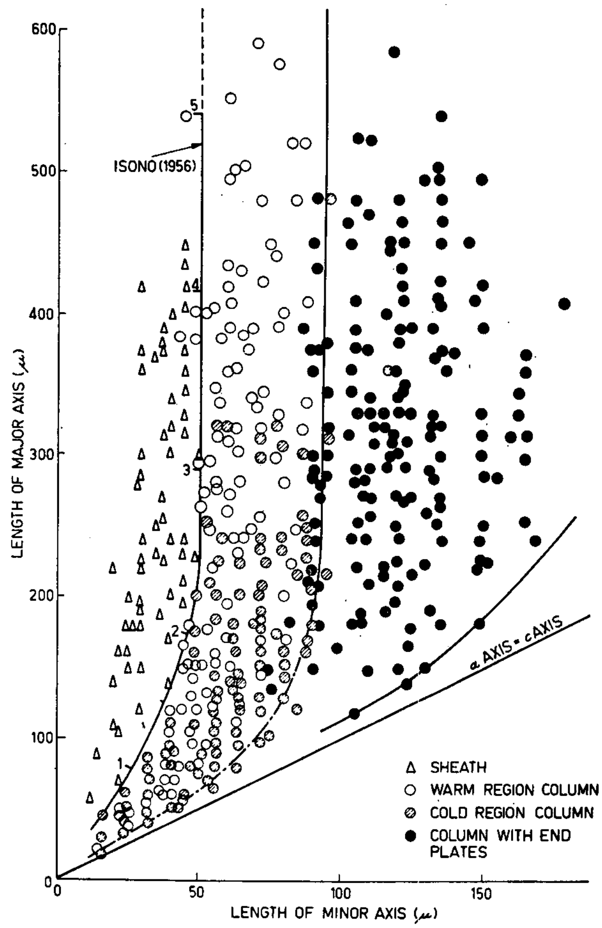


FIG. 5. Relation between the length along the major axis and that along the minor axis of columnar crystals. The full lines have been used to mark the boundaries between the various groups of ice crystals. The full line for sheath crystals agrees with the maximum growth curve obtained by Isono *et al.* (1956) and the figures on the curve are the growing time in minutes obtained by them.

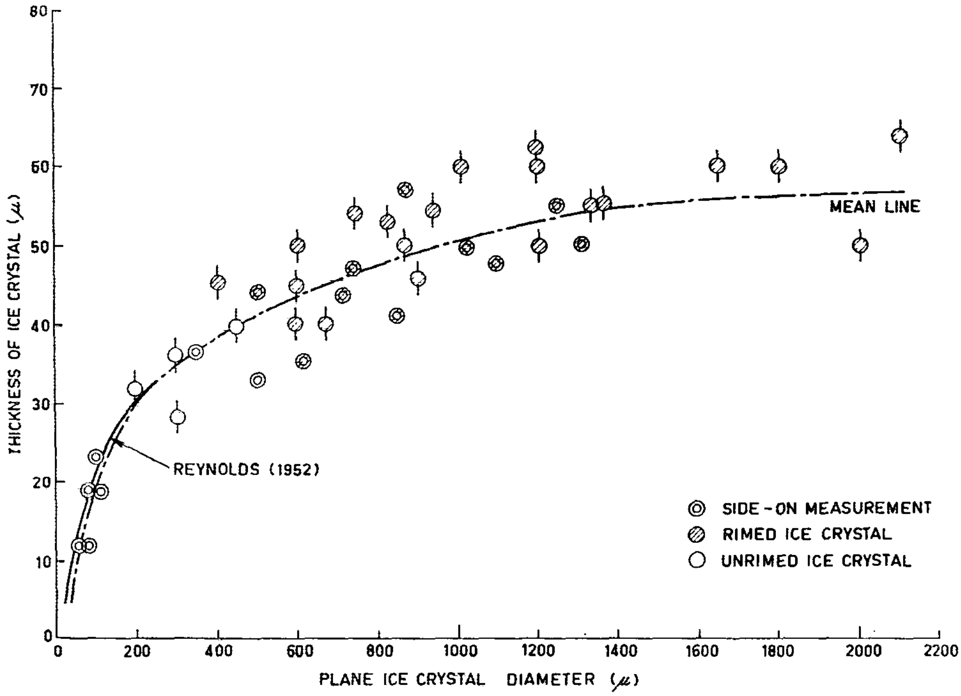


FIG. 6. Relation between the thickness and diameter of plane ice crystals. The double circles indicate side-on measurement of crystal thickness; hatched circles, rimed crystals; open circles, ice crystals without riming. The experimental results of Reynolds (1952) are plotted for comparison.

The same tendency is seen in the case of warm-region columns and cold-region columns. The growth of both axes increases until the minor axis reaches about 90 $\mu$, after which growth is virtually confined to the major axis.

This change in the characteristic growth shape cannot be accounted for in terms of changing temperature of growth, seeing that it appears to be a consistent phenomenon regardless of the temperature at which the columnar crystals were sampled. Rather, it appears that for falling columns the boundary layer is very much thinner over the basal faces than over the prism faces where growth virtually ceases.

As shown in Fig. 5, the ratio of the major to the minor axis in the column with end plates (considering only the columnar part of the crystal) is quite different from the same ratio in columnar crystals.

According to Magono and Lee (1966), the column with end plates can be classified as a transitional form originating as a column at temperatures $<-20$C and growing end plates at temperatures between $-20$ and $-18$C. This is consistent with the present case. The ice crystals were sampled at temperatures in the vicinity of $-15$C in clouds of top temperatures between $-20$ and $-25$C.

The striking feature of these crystals is not only the formation of end plates at the basal faces of the columns but also the enhanced growth along the minor axis. It is obvious that growth is not governed in this instance by ventilation, but that an overriding part is played by temperature-dependent surface migration which favors growth along the minor axis rather than the major.

As we shall discuss in the next section, this rapid growth along the minor axis makes the riming process much easier. All the columns with end plates sampled in mixed clouds were heavily rimed (see Fig. 4).

*b. Plate ice crystals*

Plate crystals have less mechanical strength than columns, so it is more difficult to prevent them shattering in the collection process. By slowing down the air to about 15 m $sec^{-1}$ relative to the aircraft, using a decelerator, the shattering of plane ice crystals was considerably reduced. Plate crystals up to 400 $\mu$ in diameter could be replicated intact, but dendritic crystals $>500\,\mu$ were usually broken.

To study the relationship between the diameter and thickness of plate crystals, the thickness was measured by focusing on the top and bottom of the crystal replica and reading the displacement on the calibrated fine-adjustment of the microscope. A more reliable method is to make a direct measurement from the side view of the crystal, though it is rare to find crystals replicated in such a way that this is possible.

The relationship between thickness and diameter of plane ice crystals is shown in Fig. 6, the double circles indicating side-on measurements of crystal dimensions.

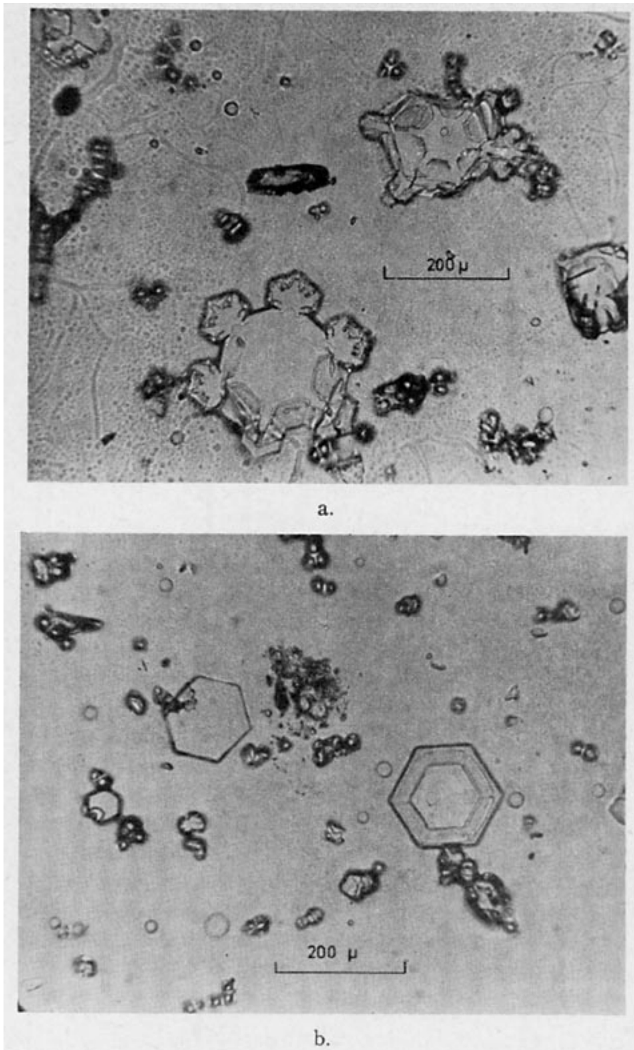


FIG. 7. Hexagonal plate ice crystals, a., which had begun to sprout dendritic growths at the corners and, b., without sprouts at corners. Observed simultaneously at about −15C, 15 October 1966.

As the ice crystals grow in diameter so the thickness tends to a more or less constant value between 50 and 60 μ. For small plane crystals our results agree well with the cloud chamber experiments of Reynolds (1952). The thickness of plane dendrites obtained by Nakaya and Terada (1935) is on the average 11 μ, this value being much lower than that obtained by the present author and Reynolds (1952).

*c. The onset of dendritic growth*

As we discussed in the previous section, the growth mode of columnar ice crystals is influenced by their falling motion. Similar ventilation effects are to be expected with plane ice crystals.

On 15 October 1966, during flights through altocumulus clouds at temperatures between −12 and −15C, we sampled many hexagonal plate crystals, some of which had begun to sprout dendritic growths at the corners (Fig. 7).

We show in Fig. 8 the size distribution of ice crystals and the percentage showing dendritic growth against the overall diameter. Crystals <200 μ diameter showed no dendritic growth at the corners. The transition occurred in the range 200–300 μ diameter, and all plates >300 μ showed some signs of dendritic growth.

Mason (1953) estimates that hexagonal plane ice crystals will start to grow dendritically only if their diameter >200 μ; the agreement with present results is good. Some variation in the transition diameter is to be expected, since it will be affected by the size and concentration of water drops which act as localized sources of water vapor.

The results of this section could therefore be summarized as follows:

1) Growth along the minor axis virtually ceases in columnar crystals after it reaches a length characteristic of the crystal type. This is about 50 μ for sheath crystals and 90 μ for warm and cold region columns, but considerably larger for column with end plates.

2) As the diameter of the plate ice crystal increases, the thickness tends to constant values of 50–60 μ.

3) Dendritic growth was not found on crystals <200 μ in diameter, but it was found on all plates >300 μ in diameter.

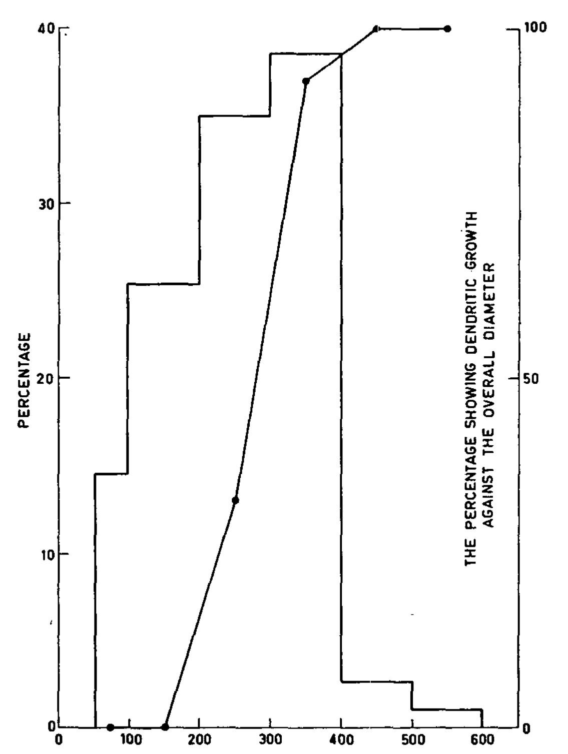


FIG. 8. Size distribution of plane ice crystals and the percentage showing dendritic growth against the overall crystal diameter.

## 4. The onset of riming

The onset of riming must be a function of the size, shape and fall velocity of the ice crystals as well as of the size of the cloud droplets.

The fall velocity of snowflakes has been measured (Nakaya and Terada, 1935) but little is known of the fall velocity of ice crystals $<100\,\mu$ in diameter. Published work on the collection efficiency of ice crystals for water drops is limited to some calculations for plates by Fletcher (1962). In the absence of any way of estimating the sizes of cloud elements which make riming possible, direct measurement is necessary; such measurements are described in this section. Crystals were classified as rimed when it was apparent from their replicas that they had accreted five or more drops. This excludes any crystals which might collide with one or two drops while on the collecting slide.

*a. The size distribution of accreted cloud drops*

The size distributions of cloud droplets accreted on columnar and dendritic ice crystals are shown in Fig. 9. The frozen droplets caught by columns (of major axis 200–400 $\mu$, minor axis 100–150 $\mu$) observed on 11 and 22 August 1966 range in diameter from 20–70 $\mu$. In the case of dendritic ice crystals of about 2 mm diameter observed on 15 October 1966, droplets range from 15 40 $\mu$. This size distribution is in good agreement with

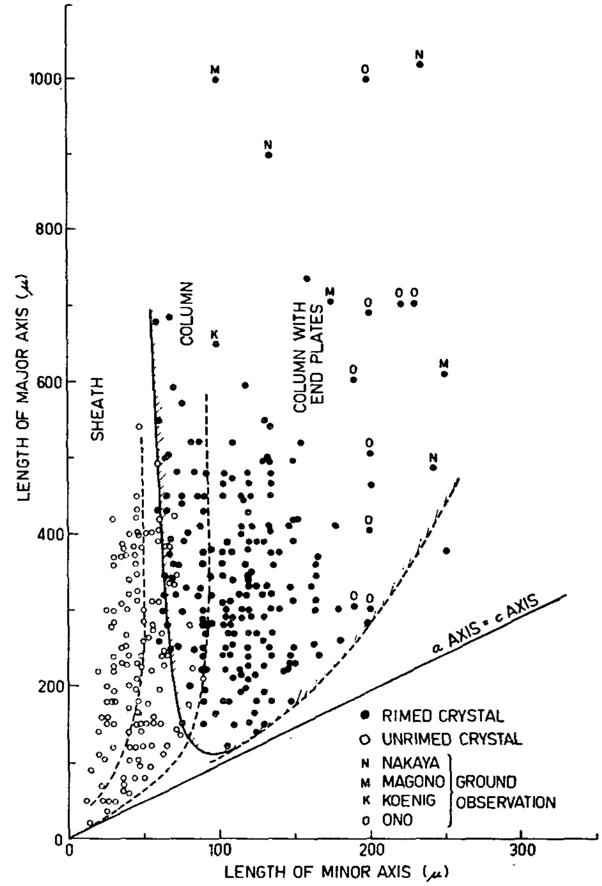


FIG. 10. Relationship between the onset of riming and the size of columnar ice crystals. Open circles represent ice crystals without riming, solid circles, rimed crystals. The size region in which riming takes place is hatched. No cold-region columns are included in this diagram.

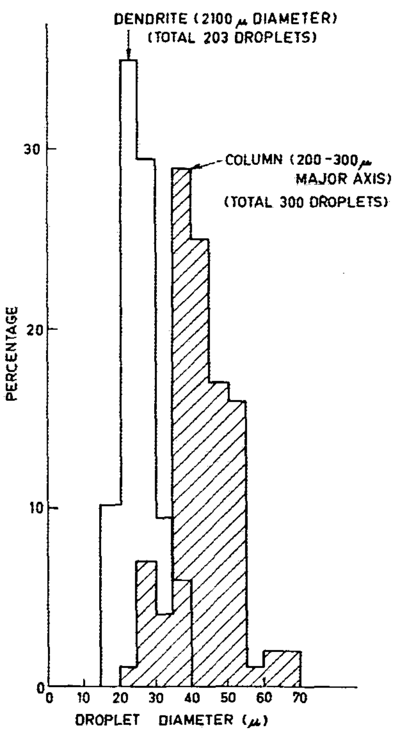


FIG. 9. Size distributions of accreted cloud droplets on column and dendrite. No correction was made for spreading of droplets on crystal surface.

that obtained by Nakaya (1954). The cutoff diameter of droplets collected by dendritic ice crystals is between 10 and 15 $\mu$, calculated from the theory by Ranz and Wong (1952), assuming the crystal to be a circular disc with fall velocity of 30 cm $sec^{-1}$. It is difficult to say whether the difference in the size distribution of droplets accreted by columns and by dendrites is due to the difference in collection efficiency. This is because of the difference in cloud conditions for both cases and the growth or evaporation of accreted droplets.

*b. The orientation of rime ice*

A typical illustration of what happens when a rimed crystal continues to grow from the vapor is shown in Fig. 4. The collected droplets of diameter 30–40 $\mu$ frozen on the prism faces of the column have grown as single crystals. Some of them have developed end plates parallel to the basal plane of the substrate. From an examination of some 200 crystals we conclude that, almost without exception, droplets accreted on the prism faces between $-15$ and $-20$C take the same

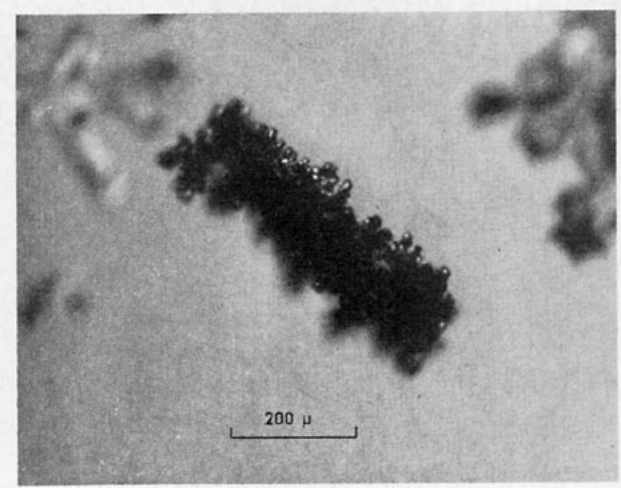


FIG. 11. Rimed column ice crystal observed on the ground, February 1964.

orientation as the substrate. This result is in good agreement with observations of Hallett (1964).

*c. The onset of riming on columnar ice crystals*

The relationship between the onset of riming and the size of columnar ice crystals is shown in Fig. 10. Open circles represent ice crystals without riming and solid circles represent rimed crystals. For comparison we include several rimed ice crystals observed on the ground by Nakaya (1954), Magono and Lee (1966) and Koenig[1]. The size region in which riming takes place is hatched. No cold-region columns are included in this diagram. Though the altostratus cloud of 11 August 1966 did contain sparse water drops (see Fig. 3) these were apparently too few to allow riming.

It is obvious from Fig. 10 that the onset of riming is markedly dependent on the length of columnar crystals along the minor axis. No riming was found in crystals with minor axes $<50\,\mu$. On the other hand, almost all crystals of minor axis $>90\,\mu$ were rimed. Between axis lengths of 50–90 $\mu$ the onset of riming is very critical and appears to be favored by increased length along the major axis. The riming of sheaths and long columns [in the classification of Magono and Lee (1966)] is very rare because their minor axes are below the riming limit. This agrees with the results of Isono *et al.* (1956) who observed many sheath-type crystals up to 500 $\mu$ in length of major axis, but with no signs of riming.

From the well-known calculations of the collection efficiency of cylinders (Langmuir and Blodgett, 1946; Ranz and Wong, 1952; Davies and Peetz, 1956) one would expect the onset of riming on columns to depend on the lengths of their minor axes. A second factor also enters in here; namely, that the fall velocity is much more sensitive to the length of the minor than the major axis (Jayaweera and Mason, 1966).

Some considerations concerning the collection efficiency of columnar ice crystals will be given in the following subsection.

*d. The onset of riming on plane ice crystals*

From the small amount of data that we have been able to collect, it appears that riming is rare on plates $<300\,\mu$ in diameter but is usual on crystals $>400\,\mu$.

We cannot estimate the collection efficiency of a plane ice crystal because we have no theoretical collection efficiency of a disc for flow at Re = 10. In the cases of plane ice crystals of diameter 200–400 $\mu$, where Re $<5$, we cannot use the results of a disc for potential flow.

Fletcher (1962) estimates that the plane ice crystal of diameter 250 $\mu$ will accrete droplets $>4\,\mu$ in diameter, but this is based upon the collection efficiency of a disc for potential flow and a doubtful assumption of a fall velocity of 50 cm sec$^{-1}$ for a plane crystal.

The results of this section could therefore be summarized as follows:

1) The onset of riming on columnar ice crystals is markedly dependent on the length along the minor axis. The onset of riming was found on columnar ice crystals with the minor axis $>90\,\mu$ but not on columnar ice crystals with the minor axis $<50\,\mu$. Between axis lengths of 50–90 $\mu$ the onset of riming was critical and appeared to be favored by increased length along the major axis.

2) The onset of riming was found on plane ice crystals $>400\,\mu$ in diameter but not on plane ice crystals $<300\,\mu$.

3) The accreted droplets of diameter 30–40 $\mu$ frozen on prism faces of the columns have grown as single

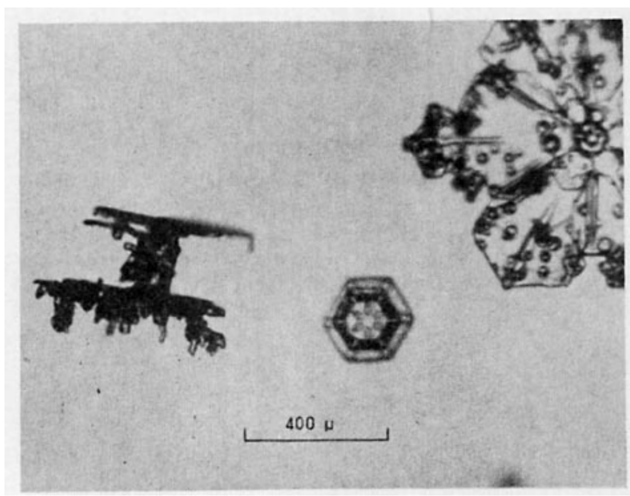


FIG. 12. Rimed column ice crystal with extended end plates observed on the ground, February 1964.

[1] Koenig, L. R., 1967: Ice multiplication in the atmosphere. Paper presented at Nucleation Conference of the Bureau of Reclamation, Denver, Colo., 10–12 July.

crystals and have the same crystal orientation at the substrate at temperature between −15C and −20C.

## 5. The orientation of freely falling ice crystals

In the riming of ice crystals the accreted drops are found to be frozen preferentially on certain crystal faces. By studying the distribution of the frozen drops we can deduce the orientation in which the crystal fell during riming. We examined crystals collected both at the ground and from an aircraft.

### *a. Columnar ice crystals*

A typical rimed column is shown in Fig. 11. Cloud droplets are accreted only on the prism faces and not upon the basal faces of the crystal. Where the column has grown only small end plates, as in Fig. 4, we still find accreted drops only on prism faces. These cases indicate that columnar ice crystals fall with their major axes horizontal.

However, when the diameter of the end plates exceeds the length of the column, as in Fig. 12, cloud droplets are accreted on one face of the end plates. This indicates that the orientation of the crystal has changed so that the major axis of the column is now vertical. The large end plates are now dominant in deciding the orientation of the crystal.

### *b. Plane ice crystals*

Typical rimed plane ice crystals of various sizes are shown in Figs. 13 and 14.

For plate ice crystals accretion of drops occurs only on the front face of the falling crystal. Even in such a case as that of Fig. 13, where there is a heavy build-up of rime on the front face of the 750-$\mu$ diameter plate, this does not affect the orientation and accretion is still confined to the front face.

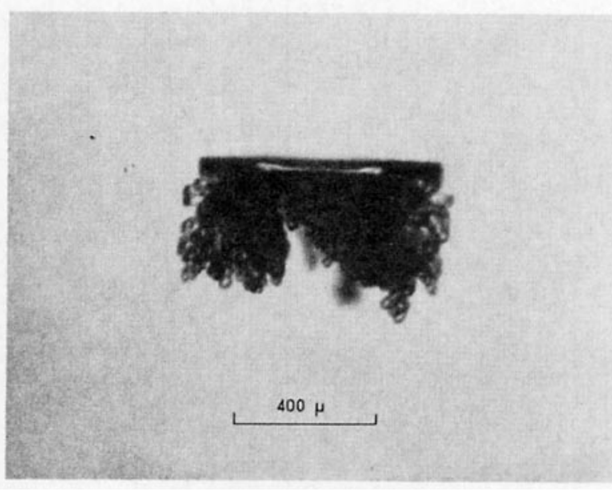


FIG. 13. Rimed plane ice crystal observed on the ground, February 1964.

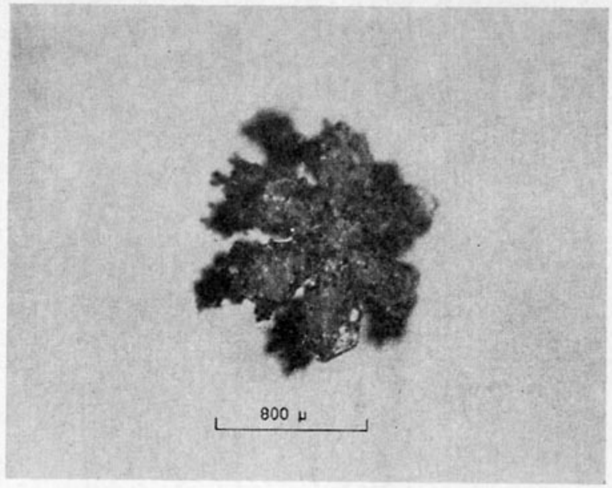


FIG. 14. Rimed broad-branched ice crystal observed on the ground, February 1964.

The dendrite in Fig. 14 is interesting in that a few droplets are accreted on the rear face, although, as with the other cases, accretion on the front face predominates.

From the model experiments on the capture of spores by discs cut from tissue paper (Starr and Mason, 1966), we may deduce that our plate crystals fell in a fixed orientation with plane horizontal. In the case of the dendrite of Fig. 14 some oscillation must have taken place. Free fall characteristics of individual plane ice crystals are summarized by Brownscombe and Hallett (1967).

Our present results on the orientation of ice crystals agree well with the results obtained from model experiments by Podzimek (1965) and Jayaweera and Mason (1966).

## 6. Discussion

It is possible to explain the observational results on the onset of riming by calculating the collection efficiency of a columnar ice crystal for water drops of various sizes.

The fall velocity must be known, and this has been estimated by Jayaweera (private communication), who worked out the fall velocity of columns of different diameters and lengths from interpolation of drag coefficients over the range of Reynolds number, $10^{-1} < Re < 10^3$, based on the available theoretical and experimental results. The assumption is then made that the collection efficiency of a column is similar to that of a cylinder, which has been calculated for Reynolds number of 0.2 and 10 in the case of a finite particle by Davies and Peetz (1956).

The collection efficiency of a column of 30 $\mu$ in diameter is calculated from Davies' curve for Re=0.2. As the Reynolds number of this crystal is about 0.2, the calculated collection efficiency should be fairly accurate. In the case of columns of 80 and 100 $\mu$ in

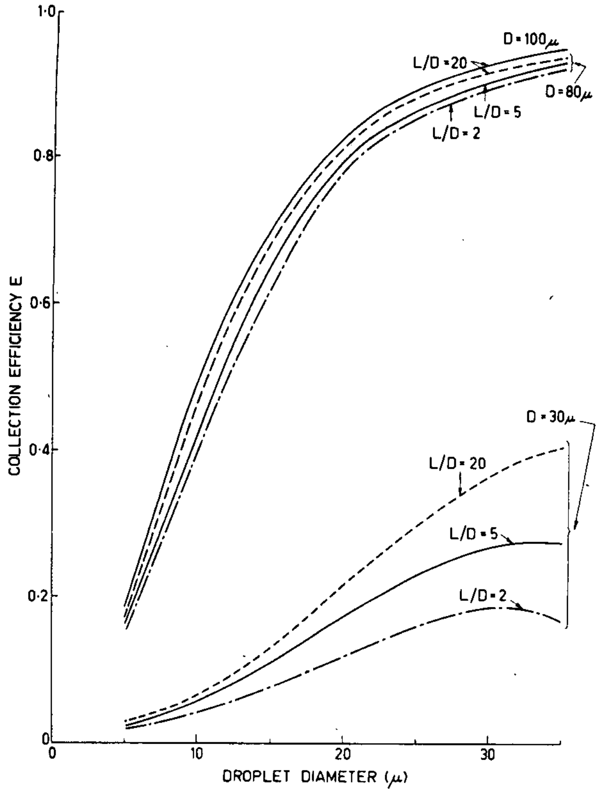


FIG. 15. Collection efficiency of columnar ice crystals (diameter and ratio of dimensions along the crystal axis shown as parameters) for cloud droplets of various sizes, calculated from the theory of Davies and Peetz (1956) assuming the crystal to be a cylinder. Fall velocity based on numerical calculation by Jayaweera (private communication).

diameter, the calculation is based on the curve for Re=10. This may overestimate the collection efficiency, especially for the column of 80 μ in diameter, because the Reynolds number of the crystal is about 2. For columns of diameter from 40–70 μ where $0.2<\mathrm{Re}<2$, we cannot estimate the collection efficiency.

The calculated collection efficiencies of columnar ice crystals for cloud droplets of various sizes are shown in Fig. 15. It can be seen that the accretion of cloud droplets to a column 30 μ in diameter is very unlikely, while the rapid increase of the collection efficiency of columns $\geqslant 80$ μ in diameter makes the accretion of cloud droplets much easier. The variation of the crystal length has little effect on the collection efficiency of columnar ice crystals, which would be expected from the fact that the fall velocity of columnar ice crystals is much more sensitive to the crystal diameter (Jayaweera, private communication). Although we cannot calculate the collection efficiency in the critical region between no riming and the onset of riming shown in Fig. 10, the calculated collection efficiency shows fairly good agreement with the observational results.

In order to clarify the conditions of the onset of riming, we would need to know the fall velocity of ice crystals $<1000$ μ and the theoretical collection efficiency for flow at $0.2<\mathrm{Re}<10$.

## 7. Conclusions

The results of this study may be summarized as follows:

1) Ice crystals grow preferentially along the "*c*" or the "*a*" axes depending on the temperature. The ratio of the two axial dimensions changes as the crystal grows. The effect of falling motion is to enhance longitudinal growth of columns and dendritic growth of plane crystals.

2) The onset of riming is controlled by crystal size. For columnar crystals the most sensitive parameter is the length along the minor axis; for plates, the diameter.

3) The crystal orientation in frozen drops accreted on the prism faces of columnar crystals at temperatures between −15 and −20C is the same as in the substrate.

4) Freely-falling ice crystals are oriented so as to present maximum resistance to motion. Columnar crystals fall with their major axes horizontal, and plate crystals their main faces horizontal; dendrites may oscillate slightly about this equilibrium orientation.

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