Properties of Columnar Ice Crystals Precipitating from Layer Clouds

K. O. L. F. JAYAWEERA AND T. OHTAKE

Geophysical Institute, University of Alaska, Fairbanks 99701

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ABSTRACT

Single unrimed columnar ice crystals (>200 μm in length) from shallow layer clouds were collected in silicone oil, photographed under a microscope, and melted to determine their mass. These ice crystals were representative of those growing in a water sub-saturated environment in the temperature range −4 to −10C. The axial lengths of the crystals were related by the expression $D=6.3\,L^{0.437}$, where D and L are the lengths of the minor and major axes, expressed in micrometers, and have a nearly constant density of 0.3 gm cm^{-3}. The habit of the ice crystals was very similar to those obtained in the water-droplet-free environment of laboratory diffusion chambers and was elementary or bundles of sheaths. Present observations suggest that bundles originate by the growth of secondary ice crystals on the prism face of the crystal. These secondary ice crystals then grow on the surface of the parent crystal and may grow at a rate faster than, and at the expense of, the parent crystal. The results of these observations were compared with those made on ice crystals growing in clouds supersaturated with respect to water.

1. Introduction

Laboratory experiments (e.g., Hallet and Mason, 1958; Kobayashi 1961) indicate that the basic habit of an ice crystal is very critically determined by the temperature, particularly near its melting point, and that supersaturation above water saturation is required for the growth of secondary features such as needle-like extensions and dendritic developments. Below water saturation such features do not exist, and, as the excess vapor pressure approaches close to that of ice saturation, vapor pressure also profoundly affects the ice crystal habit.

In-cloud collection of ice crystals from aircraft by Ono (1969, 1970) and from a mountain station within a cap cloud by Auer and Veal (1970) have confirmed the laboratory results on the temperature dependence of ice crystal habits. However, all these observations were made in clouds or in regions of clouds where the supersaturations were above that at water saturation, because the updraft speeds in the convective clouds sampled by Ono are of the order of meters per second and those of cap clouds at Elk Mountain are about 50 cm sec^{-1} (Dr. G. Vali, private communication). In layer clouds, where updrafts are few centimeters per second, it is unlikely that supersaturations above that at water saturation will exist throughout the growth of an ice crystal. Even in cumuliform clouds supersaturation situations conducive to the formation of needles may occur only within the core of the cloud corresponding to rising air masses. In general, most ice crystals, especially those that are precipitating (>200 μm in length), grow either at or below water saturation and for the temperature range −4 to −10C are expected to be hollow columns or sheaths. This investigation is an attempt to understand in detail the habit of these crystals and the mechanism of their formation together with other properties such as axial lengths and densities.

The importance of axial lengths and densities of columnar ice crystals on the terminal velocity has been demonstrated by Jayaweera and Cottis (1969) and recently by Heymsfield (1972). Their investigations indicate that the correct computations of the terminal velocities are not possible unless the aspect ratio and the mass of the crystal are known. Similar conclusions are evident for the calculated growth rates. The observed peaks in the growth rates at −5 and −15C can be attributed to the elongated growth of ice crystals at these temperatures as shown by Koenig (1971) and Jayaweera (1971). The high peak in the growth rate curves at −5C given by Jayaweera (1971) is a direct consequence of the assumption that the growth of columns occurs only in one direction after they have reached a certain size. On the other hand, if the other axis also continues to grow then these peaks will be smoothed somewhat (Koenig, 1971).

The importance of knowing the crystal dimensions and mass has been recently realized by cloud physicists. Auer and Veal (1970) have made a comprehensive study on the dimensions of crystals collected at Elk Mountain and have given empirical expressions for the best-fit curves relating crystal dimensions. Prior to

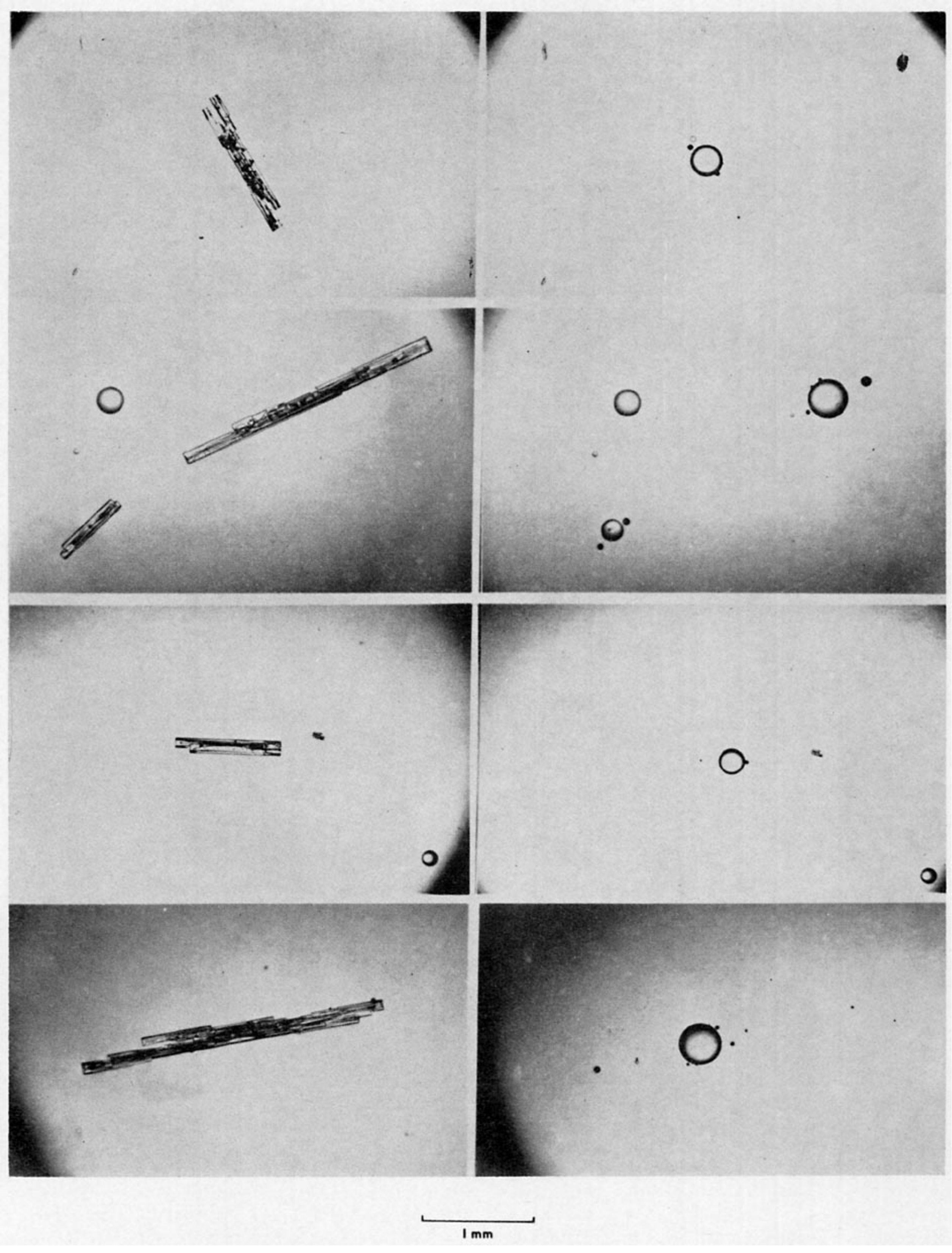

FIG. 1. Examples of columnar ice crystals before and after melting. (The extra water drops sometimes seen with the crystals were from previously melted ice crystals and not from the cloud.)

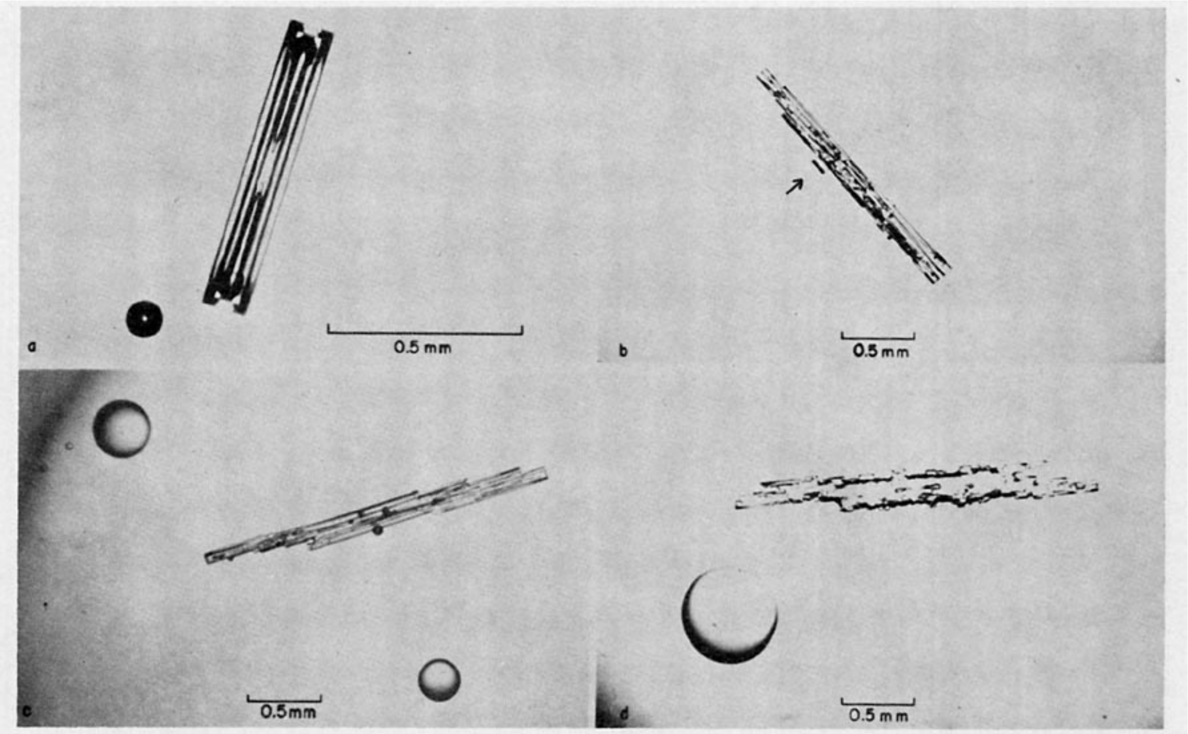

FIG. 2. Various different types of ice crystals collected under similar conditions: (a) symmetrical solid/hollow column, (b) initiation of secondary growth indicated by arrow, (c) well-developed secondary growth, (d) corrugated crystal.

their investigations, the studies on axial ratios and their results were either incomplete or confusing. Although existing results show very little quantitative agreement, they do agree qualitatively. In the initial stages of ice crystal growth, both axes grow at very nearly the same rate but as the ice crystal becomes bigger the *a*-axis accelerates its growth in relation to the other. The relative growth of the *a*-axis over the other is a strong function of the crystal habit. However, at no phase of its growth does the *c*-axis completely cease to grow.

With regard to the densities of columnar crystals our knowledge is quite limited. Perhaps the only direct measurements of densities are those estimated by Magono (1954) for needles based on the results of Nakaya (1954) and the recent results for very small columns (<100 μm in length) by Jayaweera and Ryan (1972), for rimed columns by Zikmunda and Vali (1972), and for bullets from cirrus clouds by Heymsfield (1972). Lack of density measurements have led Ono (1970) and Heymsfield (1972) to estimate the density of columns from replicas of these crystals on formvar-coated slides. The accuracy of this technique was strongly challenged by Jayaweera and Ryan (1972) who showed that such calculations can highly overestimate the density.

It is difficult to obtain data on large columnar ice crystals because of the invariable possibility of riming. Very little data exist on the way in which a columnar crystal would grow to sizes in excess of a few hundred micrometers.

2. Location and technique

In Alaska, during the winter, precipitation occurs sometimes from stratus clouds a few thousand meters in thickness. During the early and latter part of the winter these clouds sometimes have temperatures in the region suitable for columnar growth (-4 to -10C) and bases low enough so that they cover mountains or high ground. The roof of the Geophysical Institute, University of Alaska, is at an elevation of 250 m MSL and sometimes the base of such clouds reach the roof top, and only light winds are encountered. Therefore, this site is a very suitable location for sampling natural ice crystals.

The vertical extent of these clouds is difficult to determine. However, with the Fairbanks radiosonde data it is possible to estimate the extent and the temperature range of the cloud. The region where the dew point coincides with the air temperature (i.e., relative humidity 100%) is considered to be the cloud region. It must be appreciated that while a radiosonde will not distinguish between a continuous and a patchy cloud, it does indicate the existence of cloud layers and their heights. Although the vertical extent of these clouds is a few thousand meters, the low concentration of hydrometeors make them appear thin with the sun visible through the clouds.

Suitable conditions for the study of columnar ice crystals occurred three times during the early part of winter—21, 24 and 25 October. The temperature conditions on these three days were very similar, with the ground temperature between −6 and −8C, relative humidity just under 100%, and the clouds as estimated from the radiosonde data were between 1000 and 3000 m thick and the temperature ranging from −4 to −10C. Most of the columnar ice crystals precipitating from these clouds were single; a few were aggregated but no highly rimed ice crystals were seen. For our experiments we selected only the single ice crystals.

The ice crystals were collected on glass slides coated with silicone D.C. 200 oil.[1] The glass slides were then removed to a shelter where they were observed under a microscope, and a suitable crystal was selected and photographed. This crystal was subsequently melted to form a water drop and rephotographed. The melting was accomplished by using a heated wire under the base of the microscope stage. The dimensions of the crystals before and after melting were measured from the negative using a 35-mm film reader. The silicone oil used was ideal because it allowed the drops to form with very little breakup during melting. A few examples of ice crystals before and after melting are shown in Fig. 1. The air bubbles which escape from the ice crystals are sometimes trapped in the oil and can be easily distinguished in the photographs. If a breakup of the drop occurred during the melting process then the mass of all drops was taken.

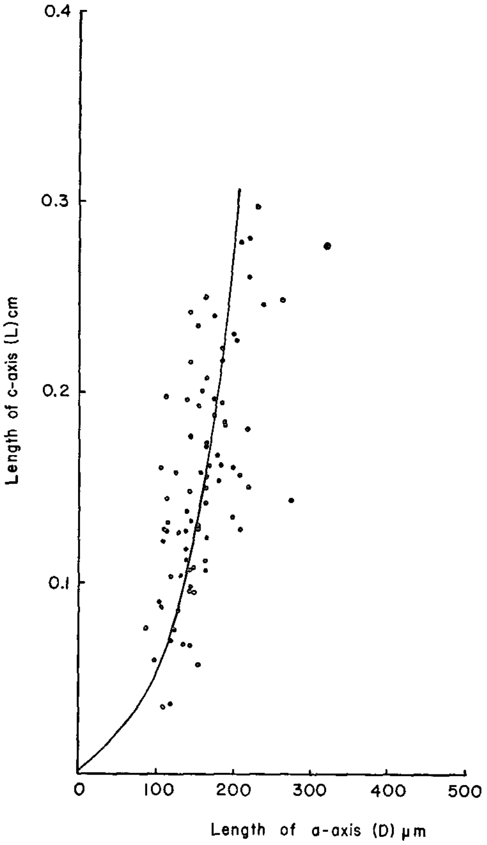

Fig. 3. Axial lengths of columnar ice crystals.

3. Results

a. General crystal structure

A few examples of the ice crystals collected are shown in Fig. 2. These crystals, together with those shown in Fig. 1, represent the various forms of columnar ice crystals that were found during the experiments. All the ice crystals fall into the two categories "elementary sheath or hollow column" and "bundles of sheaths" (Figs. 2a, b, c, d) of the Magono and Lee (1966) classification. The field observations confirm the laboratory results on the habit of columnar crystals where lack of needle-like extensions between −4 and −10C is evidence for the atmosphere being at or below water saturation.

The mechanism of the formation of bundles is not clear. Some insight to this can be obtained from some of the crystals collected. Bundle crystals appear to form from the growth of columnar ice crystals on the surface of the parent crystal. The initiation of such a growth can be seen in Fig. 2 where a small columnar ice crystal has begun to grow on the surface of the parent crystal. Such nucleation could arise due to a frozen drop or on a favorable site. An ice crystal thus nucleated on the surface may then grow on the parent crystal and sometimes dominate the growth so as to form an extension. Many such secondary crystals may eventually give the appearance of a bundle of columns where the *c*-axes are all parallel to each other.

A rather peculiar type of excessive secondary growth, presumably through riming, is shown in Fig. 2d. Ice crystals of this type appear to have a rough surface, as if sublimation has taken place. It is more likely that the sublimation occurred due to transfer of vapor from the parent crystal to the secondary crystals than by evaporation of the crystal due to its being subjected to unsaturated air; if the crystal has encountered ice-subsaturated air, it would be more likely to evaporate near the edges than on the prism face.

Our opinion is that secondary ice crystals grow at the expense of the parent crystal. If there are large numbers of secondary crystals, then there is a possibility that some of them may break away from the parent crystal. However, it must be mentioned that the crystal multiplication that could result from any such breakup

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[1] This grade of oil was chosen because a separate experiment using water drops from hypodermic needles collected in this oil showed that one to one correspondence existed between the measured and the actual diameters for drops <1 mm in diameter. Because the diameter of the drops formed by melting the ice crystals collected in our experiments were less than 1 mm, sphericity of the drops can be assumed in calculating the mass of the ice crystals.

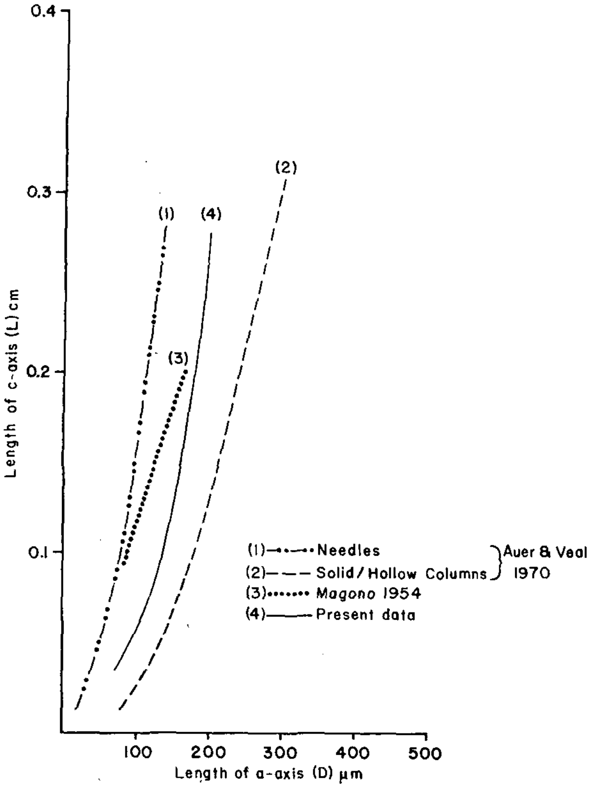

FIG. 4. Empirical relationship for columnar ice crystals obtained by Auer and Veal (1970), Magono (1954), and by the present authors.

cannot account for the high rate of multiplication observed in cumulus clouds (see, e.g., Mossop *et al.*, 1970), but will have important implications in the mechanism of growth of ice crystals and that of precipitation in layer clouds. Furthermore, the existence of secondary ice crystals can give rise to flow disturbances and microturbulence causing the crystals to deviate from the preferred orientation of fall. Such deviations and several types of rotatory motions in both the vertical and horizontal planes about the minor axis were observed by Zikmunda and Vali (1972).

b. Axial lengths

Most of the ice crystals collected are asymmetrical about the axes. The symmetric ice crystals of the type shown in Fig. 2a were very rare and occur only for the smaller lengths. Therefore, some question arises as to what is meant by the axial lengths of the crystals. It may be necessary at this stage to agree on a proper definition for the axial length. In modeling the ice phase development in clouds it is necessary to write expressions to calculate terminal velocities and growth rates of ice crystals. It has been found that for these calculations it is convenient to treat columnar ice crystals as a hexagonal cylinder. These lengths will be the maximum dimensions of the crystal along the *a*- and *c*-axes.

In Fig. 3 the length of the major axis is plotted against the minor axis. By replotting the same points on a log-log scale and using the least-squares technique, the best fit line shows that the two axes are related by the empirical relationship

$$D=6.3L^{0.437},$$

where D is the length of the minor axis and L that of the major axis. The units for both are micrometers.

In Fig. 4 we have displayed the empirical expressions of the present results with those of Auer and Veal (1970) for needles (curve 1) and solid/hollow columns (curve 2), and that of Magono (1954) for needles. These are the only available data for larger crystals (>600 μm). Since Magono's data for needles were based on very few data points, they may not be representative of their particular habit. The ice crystals collected by Auer and Veal (1970) were formed in orographic clouds where moisture is continuously fed into the cloud with the result that the cloud environment may always be above water saturation. Therefore, it is conceivable that the crystals observed by Auer and Veal grew in a region supersaturated with respect to water (Magono and Lee, 1966), giving rise to needles in the temperature region −5 to −8C and hollow/solid columns for the temperature range −8 to −10C and <−20C. On the other hand, the present results refer to the growth of ice crystals at or below water saturation in the temperature region −4 to −10C. The differences in the empirical expressions for the axial lengths for the various types of columnar growth must be taken into consideration in ice crystal modeling, and for convenience we have summarized in Table 1 the empirical expressions for the different types

TABLE 1. Empirical expressions for the growth of columar ice crystals.

	Above water saturation* (orographic and convective clouds)		At or below water saturation** (clouds formed by widespread regular and irregular ascent and below cloud base growth)		
Temperature	Habit	Expression	Temperature	Habit	Expression
−5 to −8C	needle	$D(\mu m)=1.099\ L(\mu m)^{0.61078}$	−4 to −10C	sheaths	$D(\mu m)=6.3\ L(\mu m)^{0.437}$
−8 to −10C <−20C	solid/hollow columns	$D(\mu m)=11.3\ L(\mu m)^{0.414}$			

* After Auer and Veal (1970).
** Present study.

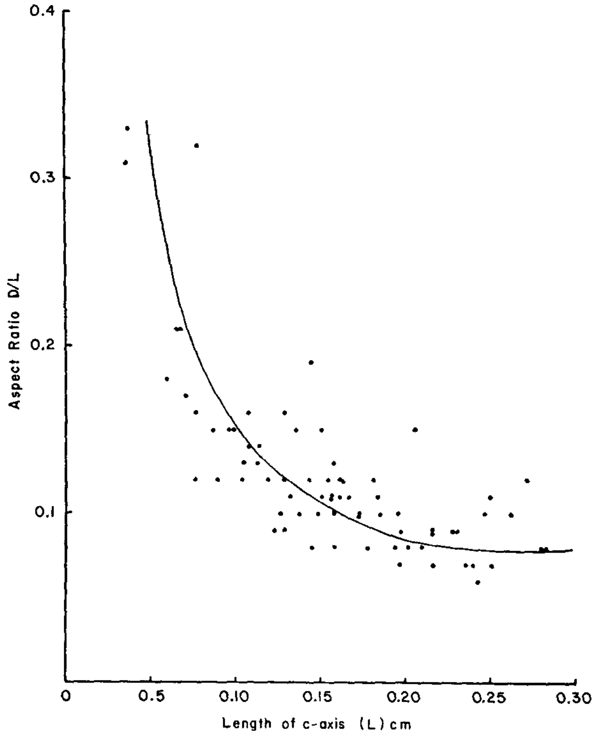

FIG. 5. Aspect ratio of columnar ice crystals as a function of length of the *a*-axis.

of columnar crystals in terms of the conditions of growth.

c. Aspect ratio

Knowledge of the aspect ratio as a function of length is of interest in many applications such as crystal modeling. Hence in Fig. 5 we have plotted this ratio as a function of length L. The aspect ratio shows a sharp decrease with initial increase in length but stabilizes to nearly 0.1 for lengths >2 mm.

d. Crystal mass or densities

The mass of the crystals calculated from the drop diameter of the melted crystal and the volume of the encompassing hexagonal cylinder is plotted in Fig. 6. The relationship is remarkably linear for all the crystals we observed, indicating that the bulk density of ice crystals is nearly constant at 0.3 gm cm^{-3}. The constancy of density for the warm temperature columnar crystals seems to be a common feature. The calculation of densities for needles by Magono (1954) based on the measurements of mass and dimensions given by Nakaya (1954) gives a value of 0.15 gm cm^{-3} independent of size. Recent measurements of the density of heavily rimed columns by Zikmunda and Vali (1972) indicate that it is constant at 0.3 gm cm^{-3}. Therefore, there is reason to believe that the densities of columns tend to remain constant after they reach a few hundreds of micrometers in size; but the value is determined by the conditions under which the crystals have grown.

Scarcity of density values for sheath ice crystals makes it difficult to compare our value with any other. We may perhaps make a comparison with those estimated by Ono (1970). Even though Ono's values are confined to crystals <600 μm in length, it is very unlikely that his method of evaluation of density would have given a low value of 0.3 gm cm^{-3} for larger crystals. A curve for the density of sheaths given by Ono shows very little decrease with length and has a value of 0.7 gm cm^{-3} at 600 μm length. We may therefore agree with the contention of Jayaweera and Ryan (1972) that density estimates from replicas are too high, and that the technique is thus not appropriate. The high values obtained by the method followed by Ono reflects the possibility that the crystals have much hollow structure that is apparent from its replica. Therefore, it may be necessary to be cautious in inferring the crystal structure from the replica as they may not reveal the exact structure of the crystal.

4. Conclusion

Ice crystals that grow in a water-subsaturated environment in free fall within the temperature range of −5 to −10C tend to form sheath ice crystals, very

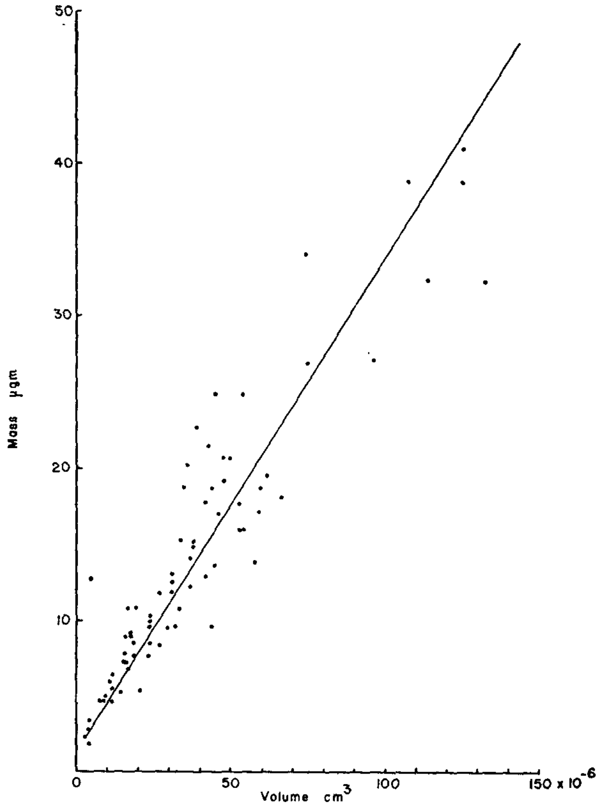

FIG. 6. Columnar ice crystal mass as a function of the volume of the encompassing hexagonal cylinder.

similar to those obtained in a water-droplet-free environment in laboratory diffusion chambers. The axial lengths (μm) of these crystals are related by the expression $D=6.3L^{0.437}$, and have a nearly constant density of 0.3 gm cm^{-3}. The bundle-like structure appears to originate from secondary ice crystals formed on the prism face of the crystal. These secondary ice crystals may have been initiated by a capture of a water droplet or by a favorable site for ice nucleation. Secondary ice crystals, at least initially, grow at the expense of the parent crystal near the surface of contact. It may be possible that if there are large numbers of secondary crystals that some may break away due to the weakening of the bond that connects the two crystals. Although the breakup of secondary crystals is not sufficient to account for the multiplication of ice crystals in cumulus clouds, it can be important in layer cloud precipitation mechanisms and in the growth and fall patterns of ice crystals.

In this work we have confined our study to columnar ice crystals only. The mechanism for the formation of dendrites which are common in these layer clouds will be studied in the future. If the supersaturation conditions required for dendritic growth are as high as those from laboratory experiments, then these crystals can never occur in layer clouds. The fact that they are present may be that the fall velocity or ventilation effectively increase the supersaturation for growth. We hope, by observing large numbers of natural dendrites in layer clouds, to obtain useful information for the initiation of and dendritic growth on ice crystals.

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