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Formation Mechanisms of Eighteen-Branched Snow Crystals

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Abstract

During the work involving snow crystals of low temperature types at Inuvik (68°22'N, 133°42'W), Northwest Territories, Canada, eighteen-branched snow crystals were observed under relative warm temperature conditions on January 8 and 11, 1986. The formation mechanisms of these crystals were discussed in terms of rotation twinning on the basis of the concept of coincidence-site lattices which was first introduced into the formation mechanisms of twelve-branched snow crystals by Kobayashi and Furukawa (1975). However, the mechanism of rotation twinning could not always applied to the eighteen-branched snow crystals.

A new idea based on freezing experiments of supercooled water droplets was introduced to the formation (Uyeda and Kikuchi, 1978). These experimental results showed that when the supercooled water droplets were frozen by means of contact with ice crystals, the supercooled water droplets froze and had a several parallel straight cracks surrounding the droplets in a vertical direction to the principal axis of the frozen droplets. Further, numerous tiny air bubbles appeared around the cracks. Therefore, it was considered that when the cracks were formed simultaneously on the surface of droplets, a horizontal rotation around the cracks arose. After which the dendritic branches grew from the droplets in the temperature conditions suitable for dendritic growth. As described above, it was considered that multi-branched snow crystals including twelve- and eighteen-branched snow crystals were formed from the freezing of supercooled cloud droplets.

1. Introduction

Twelve-branched snow crystals were observed by Doi (1833, 1840), Bentley and Humphreys (1931), Nakaya (1954) and many workers. There were few discussions, however, about the formation mechanisms of twelve-branched snow crystals. Regarding the formation mechanisms the crystals, Nakaya (1954) considered that they consisted of two overlapped dendritic crystals, that is to say, a "snowflake theory" based on a macroscopic view point. On the other hand, Kobayashi and Furukawa (1975) thought that they were formed by a "rotation twinning theory" based on the concept of coincidence-site lattices by a microscopic view point. In this paper, we will describe the formation mechanisms of eighteen-branched snow crystals, especially regarding the propriety of the rotation twinning theory in the eighteen-branched snow crystals.

2. Observations

One of the authors (K.K.) and his party were at Inuvik (68°22′N, 133°42′W), Northwest Territories, Canada as shown in Fig. 1 for forty days from December 1985 to January 1986 for the purpose of observations of "The Studies on the Snow Crystals of Low Temperature Types and Arctic Aerosols". During the observation period, a minimum temperature of −47.5℃ was recorded. On January 8 and 11, 1986, however, under relative warm temperature conditions, the eighteen-branched snow crystals were observed including typical dendritic crystals and twelve-branched snow crystals. Figures 2 to 5 show examples of multi-branched snow crystals taken by photomicroscope with a green filter and sensitive color plate at Inuvik. Figure 2 shows one of typical examples of eighteen-branched snow crystals. As seen in Fig. 2, the crystal shows an exact centered one. Figures 3 to 5 show a twelve-branched crystal, snowflakes consisting of a twelve-branched crystal and one dendrite, and eighteen-branched snow crystals. During the observation period, eight crystals were microphotographed. Regarding the eighteen-branched snow crystals, only one crystal in the Nakaya's book (1954) was recorded. However, the crystal is an off-centered, therefore, a centered, symmetric complete and beautiful crystal as

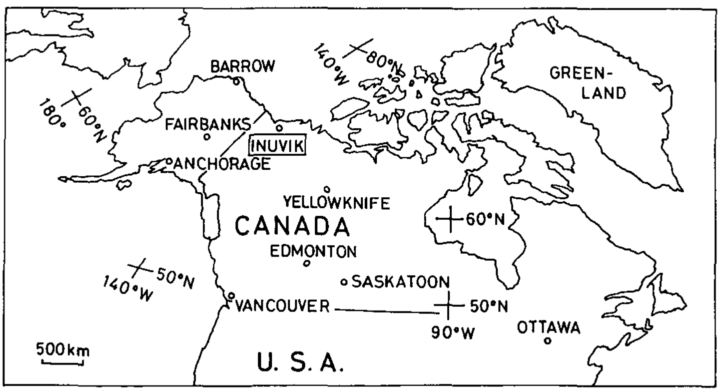


Fig. 1 Location of the observation station.

Fig. 2 An example of typical eighteen-branched snow crystals.

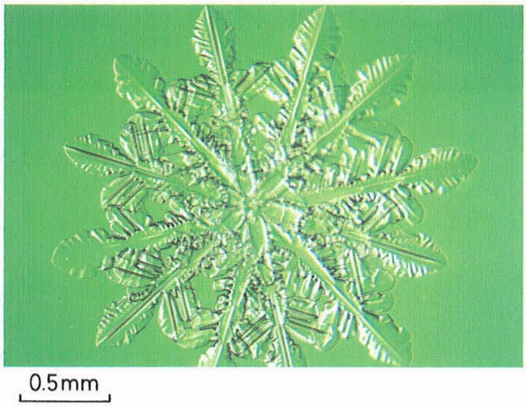


Fig. 3 An example of twelve-branched snow crystals.

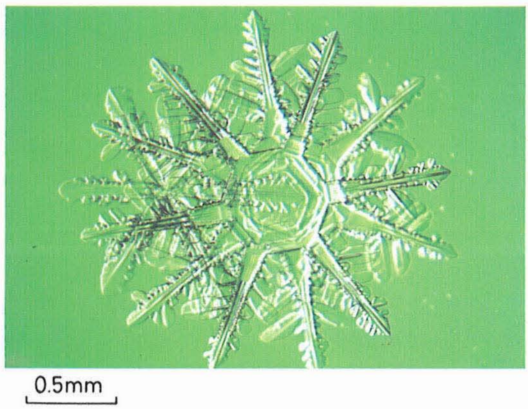


Fig. 4 A snowflake consisting of twelve-branched snow crystals and dendritic crystal.

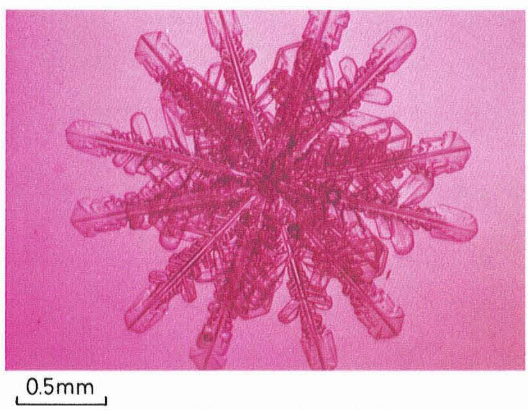


Fig. 5 An example of eighteen-branched snow crystals.

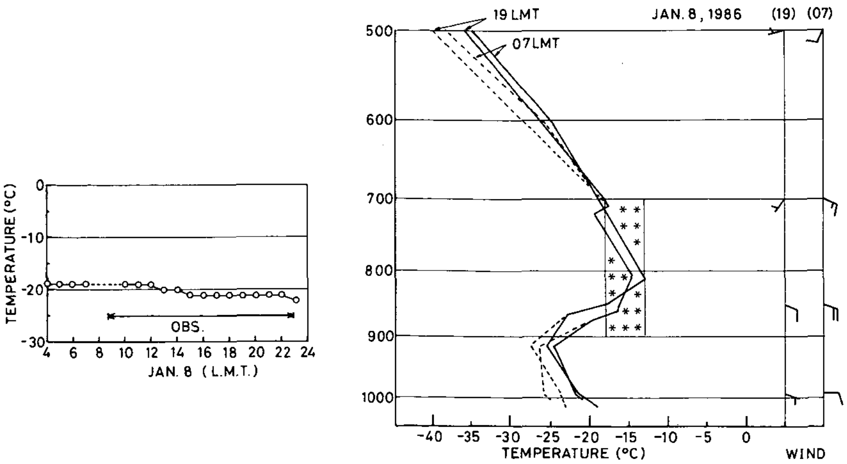


Fig. 6 Time change of surface air temperature and sounding curves on January 8, 1986 at Inuvik Weather Station, Northwest Territories, Canada.

shown in Fig. 2 is the first in the world. Figure 6 shows the time change of the surface air temperature and vertical air and dew point temperature distributions obtained at 07 and 19 L.M.T. recorded by radio soundings at Inuvik Weather Station, the Environmental Bureau of Canada. As seen in the left hand figure, the surface air temperature was recorded from −19℃ to −21℃ during the observation period. It is understood that this temperature range is close to that of dendritic growth. As seen in the right hand figure, on the other hand, there is a water saturation layer approximately from 880 to 700 mb level as shown by asterisks. The air temperatures at 07 and 19 L.M.T. of this layer are from −13℃ to −18℃. The temperature range is exactly close to that of dendritic growth. Below the water saturation layer, the minimum temperatures are −25℃ at 07 L.M.T. and −24℃ at 19 L.M.T. As estimated by the Ta-$\Delta\rho$ diagram for the snow crystal habit by Kobayashi (1961), "solid prisms" and "hollow prisms" will grow below water saturation and "sheaths" above water saturation under the conditions below −22℃. However, no prism type crystals, that is, "stellar crystal with columns" and "stellar crystal with scrolls at ends" (Magono and Lee, 1966) were observed on the ground surface. It is understood from the sounding curves as shown in Fig. 6 that there was a dry layer below 900 mb level to the ground surface. In the sounding curves, solid lines and dotted lines show the air and dew point temperatures, respectively. As seen in Figs. 2 to 5, the external dimensions of the multi-branched crystals and dendrites observed simultaneously were relatively large and were 3 mm or more approximately. The reason why the crystals were large is thought to be that the water saturation layer for dendritic growth was very thick as described above. Furthermore, it is important to recognize that the relatively large frozen cloud droplets and dendrites with frozen cloud droplets with spikes and cracks, and double plates were observed at the same time.

3. Analyses

As described previously, Kobayashi and Furukawa (1975) have explained

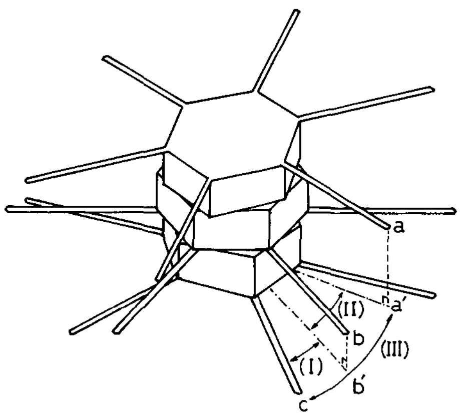


Fig. 7 Schematic arrangement of eighteen-branched snow crystals.

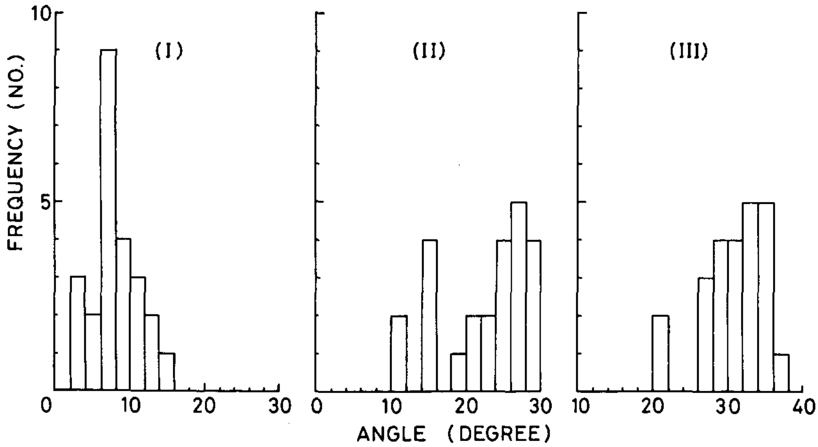


Fig. 8 Frequency distributions of angles (I), (II), and (III) of each crystal component.

the formation mechanism of twelve-branched snow crystals using the rotation twinning theory based on the concept of coincidence-site lattices. Thus, the authors have attempted a trial to apply their theory to consider that formation mechanisms of the eighteen-branched snow crystals. Figure 7 shows a schematic arrangement of the crystals. As a matter of convenience in this figure, the smaller angle (b′ − c), the larger angle (a′ − b), and the total angle (a′ − c) were named (I), (II), and (III), respectively. Frequency distributions of each angle are shown in Fig. 8. As the angle (III) is invariably smaller than 40°, the peak of angle (III) is found in range between 33° and 36°. Further, it is recognized that the peaks of angles (I) and (II) are 7° to 8° and 27° to 28°, respectively.

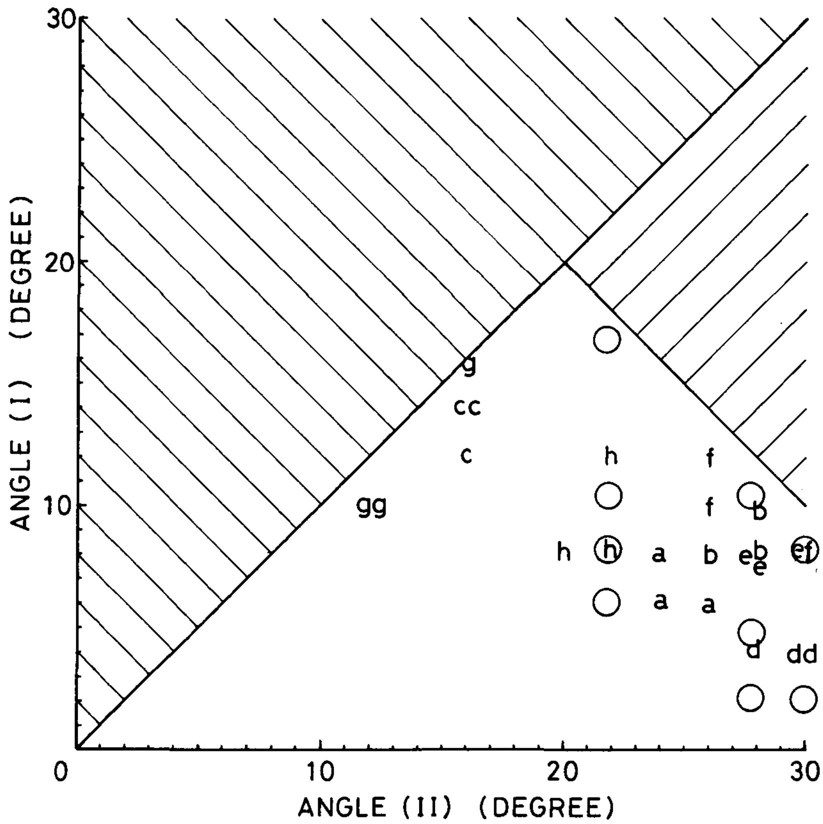


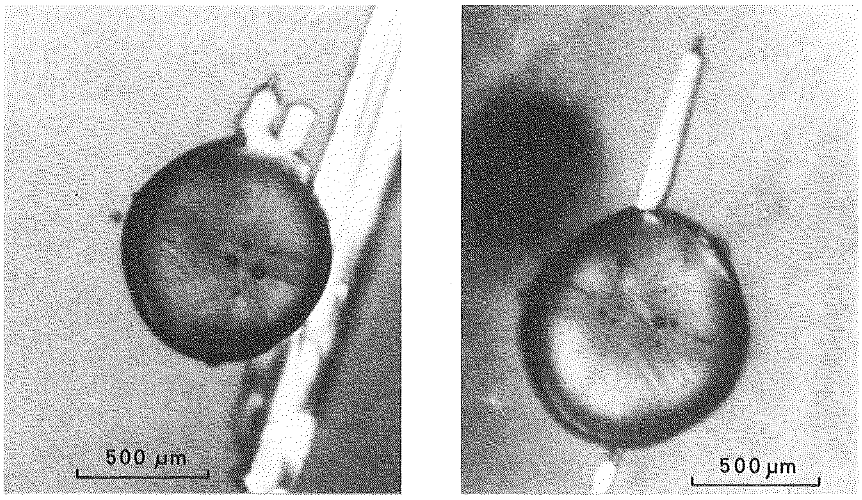
Fig. 9 A relationship between the angle (I) and the angle (II).

4. Consideration

Based on these data, the authors have attempted a trial to apply the rotation twinning theory into the eighteen-branched snow crystals. According to the Table 1 of Kobayashi and Furukawa's paper (1975), the rotation angles which are expected from relatively small multiplicity (Σ) which is a measure of the energy at the interfacial boundary are 22°, 28°, and 30°. The results when these angles were applied to the upper (a), middle (b), and lower branches (c) are shown as open circles in the Fig. 9. As the angle (I) is smaller than 20°, and the angle (II) is larger than 10°, a relationship between the angle (I) and the angle (II) is included on the outside of the shaded region. Alphabetical letters (a) to (h) mean each eighteen-branched crystal analyzed. As the same letter is three, the angles (I) and (II) are three for each crystal. Therefore, the concentration of the same letter means the centered crystal. As seen in the Fig. 9, the crystals named (a) to (e) are centered and the crystals named (f) to (h) are off-centered. As clearly seen, the relationship between positions which are expected by the rotation twinning and positions which are measured in each crystal does not coincide with each other. Especially, the relation between the angles (I) and (II) of typical crystal which was shown in Fig. 2 is shown as the letter (c) in Fig. 9, and the angles are far from the angles which are expected by the theory. Thorefore, it is concluded that the formation mechanism of eighteen-branched snow crystals can not be explained by the rotation twinning theory completely.

Thus, we should discuss a definition which can be applied to the rotation twinning by Kobayashi and Furukawa. They gave a definition that the ratio of the distance between the two centers of each component crystal to the maximum diameter of the component crystals (d) is smaller than 0.05 for the twelve-branched crystals. As well known the maximum diameter of multi-branched snow crystal and dendritic crystals is larger than 3 mm, occasionally they will become 10 mm in diameter. Therefore, if the maximum diameter of multi-branched crystals was approximately 3 mm, the ratio (d) will be 150 μm. As clearly, it is concluded that it is difficult to explain a 150 μm of the difference of the two centers of each crystal component by the rotation twinning theory.

Then, we are seeking other formation mechanisms for the multi-branched crystals. As one mechanism, there is a result obtained by the freezing experiments of supercooled water droplets frozen by the contact of fragments of snow crystals carried out by the present authors (Uyeda and Kikuchi, 1978). Figure 10 shows the typical freezing features. Figure 10 (a) and (b) are the results



(a) (b)

Fig. 10 Freezing features of supercooled water droplets.
(a) Freezing by the contact of prism plane.
(b) Freezing by the contact of basal plane.

frozen by the contact of prism plane, and of basal plane of needle type crystals, respectively. As soon as the droplets are frozen by the contact of snow crystals, spicules and spikes are formed in parallel to the principal axis of seeding crystals. As may be expected from these examples, the principal axes of frozen droplets would be in the same direction as the seeding crystals. After the completion of freezing, several cracks are normally formed to the principal axis and are encircled by the droplets completely. Following this a number of air bubbles are projected from the cracks. Therefore, it is speculated that some of cracks separate the frozen droplets into several parts. At the same time, the several parts rotate at small angles along the cracks and shift a short distance horizontally. After which the several parts freeze at that position. Therefore, if a supercooled cloud droplet is frozen by contact of the fragments of snow crystal, it would be separated into three parts normal to the principal axis, and would be rotated at small angles from each other, and the frozen cloud droplets will grow into a centered eighteen-branched crystals under the conditions of dendritic growth. Further, if the droplets are rotated at small angles and are shifted to short distances from each other, the droplets will grow to an off-centered eighteen-branched crystal. As a matter of fact, in the case where the droplet is frozen and separated into two parts, in the same manner as described above, a centered twelve-branched crystal will grow when the droplet is rotated alone, and an off-centered twelve-branched crystal will grow when the droplet is rotated and shifted. It is important to remember the facts described previously in which we observed a number of centered and off-centered twelve-branched snow crystals, frozen cloud droplets with spikes and spicules, and with cracks and double plate crystals simultaneously when we observed the eighteen-branched crystals. Further, there is a similar mechanism to form the multi-branched snow crystals. As described previous paper (Kikuchi, 1972), it is by no means rare that the sintered frozen cloud droplets are observed in the polar regions. As seen in the Figures 1 to 3 in his paper, it was frequent to connect frozen cloud droplets in the atmosphere. If three frozen cloud droplets are connecting straightly but having different principal axis and sintering, the droplets will grow into a centered eighteen-branched crystals under the conditions of dendritic growth. Therefore, it is considered that the "frozen cloud droplet theory" is effective as one of the formation mechanisms of the multi-branched snow crystals similar manner to "snowflake" and "rotation twinning" theories.

5. Conclusions

A formation mechanism for the multi-branched snow crystals including the twelve- and eighteen-branched snow crystals was discussed based on the relationship between angles of (I) and (II) of each component crystal and compared with the rotation twinning on the basis of the concept of coincidence-site lattices introduced into the formation mechanisms of twelve-branched snow crystals by Kobayashi and Furukawa (1975). As a result, it was concluded that the mechanism of rotation twinning could not always be applied to the eighteen-branched crystals. And thus, a new idea of "frozen cloud droplet theory" was introduced. Especially, the new theory can be applied to both centered and off-centered crystals. In the case of centered crystals, the distance between the two or three centers of each component crystal should be smaller than the maximum diameter of frozen cloud droplets. Therefore, when the distance is larger than the maximum diameter of frozen cloud droplets, the snow crystals are not multi-branched crystals but are snowflakes.

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