Ice

By the late Dr. A. E. H. Tutton, F.R.S.

THE subject of Sir William Bragg's Friday evening discourse at the Royal Institution on March 18 last is one which is of deep interest from a remarkable variety of points of view,

being the British members of the International Commission of Ice and Snow, which deals with the survey of glaciers and the prevention of catastrophes due to them. One of the latest discussions at the London meeting of the Association concerned "The Structure of Flow of Glacier Ice".

One property of ice, its crystal form and structure, and especially the system of symmetry to which it belongs, has, however, now after long discussion been settled, a satisfactory conclusion mainly derived from the X-ray analysis of ice crystals, which we owe largely to Sir William Bragg himself. For ice is now definitely known to crystallize in the hexagonal system, and in the holohedral class exhibiting the full symmetry of that system, the dihexagonal bipyramidal. A whimsical, yet very beautiful, illustration of this fact is afforded by one of the exquisite photographs of snow-flakes taken in a severe winter on the other side of the Atlantic by Mr. Wilson Bentley, one of the four thousand which we owe to his genius, no two of which are alike while all exhibit the same symmetry. For this particular snow-flake, of the plate-like rather than the feathery star-like kind, resembles almost ridiculously closely a grandfather-clock face in its case, with twelve markings very like Roman numerals, in exactly the positions of the twelve hours. These twelve markings correspond to the dihexagonal character of the crystal; for if the symmetry had been merely trigonal, as so long supposed, one would have expected the markings to have been only six, corresponding to ditrigonal symmetry.

The crystallographic facts now definitely known regarding ice crystals, due to the work of Dennison, Sir William Bragg and Prof. Barnes, may very briefly be stated. The space-group is D_6^4 , corresponding to the class already mentioned. There are four molecules of water in the unit cell of the structure, the dimensions of which are $a = 4.53$ A., $c = 7.41$ A. The ratio of the axes is $c : a = 1.634$. This structure remains unchanged for all temperatures between 0° C. and -183° C. The density of the crystals is 0.9168, and their cubical expansion coefficient is 0.00016.

Fig. 1.

among them that of the crystallographer, the physicist, the geologist, the climber, the ski-runner, the plumber, the food purveyor and distributor, and even the very housewife herself. Moreover, it is one which has proved of unusual difficulty, although it concerns natural phenomena of the most familiar kind and one of the most abundant substances in Nature. Indeed, we never seem to get a thorough and complete understanding concerning the extraordinary nature and unusual properties of ice, although they have been investigated and discussed for ages. Only quite recently, an Association for the Study of Snow and Ice has been formed in Great Britain, now numbering about eighty members, the nucleus

Sir William now regards the ice crystal as a set of parallel sheets of puckered hexagons, as shown in the photograph of a model reproduced in the upper part of Fig. 1, the observer being supposed to be looking along the optic (hexagonal) axis, perpendicularly to the basal plane. The sheets are connected by links perpendicular to them. The balls in the photograph (and model) are supposed to be oxygen atoms; for as hydrogen has so little effect on X-rays owing to its extreme lightness, the position of the hydrogen atoms is even yet not quite certain, although there is great probability that they lie between the oxygen atoms alternately with them, in such a manner as causes the hydrogen atoms to be double in number to the oxygens. The second photograph in the lower half of Fig. 1 was taken at right angles to the upper one, showing two sheets, the observer looking along the basal plane. Each oxygen atom lies at the centre of a tetrahedron, of which the four corners are occupied by other oxygen atoms. The distance between adjacent oxygen atoms is 2.74 angstrom units, whether in the same sheet or two neighbouring sheets.

Sir William directs attention to some singular experiments in 1936 by McFarlan, as to the effect of pressure on the structure, from which it would appear that under high pressures ice changes its structure somewhat, forming in succession two different forms, II and III, and two other photographs were shown in the lecture, reproduced in Fig. 2, of form II. While the sheets remain much the same, they are brought nearer together by the pressure, as shown in the lower half of Fig. 2. In form III the sheets also give way.

Tamman in 1910 first observed this remarkable fact, and showed that the forms II and III are solids at the low temperature of liquid air, by actually removing them from the steel high-pressure cylinder after releasing the pressure. The new solids rapidly changed into ice, with a large increase of volume, at the ordinary atmospheric pressure. Bridgman in 1912 confirmed Tamman's facts, using pressures up to ten thousand kilograms per square centimetre. McFarlan has taken the matter further by obtaining X-ray analyses of these two forms II and III, at the low temperature of -155°C ., and concludes that they are polymers of ice, having eight molecules of water to a side-centred orthorhombic cell in the case of II and sixteen molecules to a body-centred orthorhombic

cell in the case of III. McFarlan appears to have found pressures up to 2100 atmospheres adequate for the production of these two new forms of solid water. He gives the space-group of II as $V^s-C 222_1$, and the cell dimensions $a = 7.80 \text{ \AA}$., $b = 4.50 \text{ \AA}$., and $c = 5.56 \text{ \AA}$.; and for III the space-group V^s-Ibam , and the dimensions $a = 10.20 \text{ \AA}$., $b = 5.87 \text{ \AA}$., and $c = 7.17 \text{ \AA}$.

The slip or glide-plane of ice, made known in

Fig. 2.

1891 by the work of McConnell of Cambridge, a frequent visitor to Davos for health reasons, and fully confirmed by all recent work to be parallel to the basal plane, is due to the readiness with which the sheets of hexagons, although puckered, can glide over one another. Moreover, water freezing in an open pond or vessel crystallizes as a plate parallel to the basal plane. Hence McConnell, in order to test the plasticity of single ice crystals, cut some bars of ice from single crystals from a frozen lake surface, the bars being several inches long and an inch or so wide and deep. Each was supported in turn near its two ends, and a weight was suspended by a loop from its middle. When the bar had been cut with its

length parallel to the basal plane and the water surface, and was arranged on the supports with its upper surface also horizontal, parallel to that same plane, a little bending occurred when the weight was placed in position; but it was only elastic bending, and the original position was restored on removal of the weight. If the bar were turned over on its other side, with the basal plane now vertical, practically no bending at all occurred on adding the weight. But if the bar had been cut from a very thick plate of pond ice, so that its length could be made to be perpendicular to the basal plane, then on adding the weight the bar sagged continuously in the middle, taking a V-shape with a more and more acute angle, owing to the glide plane having full freedom of action, the sheets of hexagons readily gliding past each other. The deformation was, moreover, permanent to almost the complete extent. Indeed it seemed at first as if this newly discovered property of the glide plane might afford a better explanation of the

Fig. 3.

movement of glaciers than regelation. For a glacier is a conglomerate of single crystal grains, closely fitting together, with irregular bounding surfaces instead of crystal facets.

Even this was not the only additional factor required to supplement the inadequate regelation principle of Faraday (the freezing together of freely floating pieces of ice on contact) and Thomson and Tyndall (the liquefaction under pressure and re-freezing on removal of the pressure). For the crystal grains are usually promiscuously orientated, neutralizing each other's glide-plane movements. But subsequent researches showed that the irregular bounding surfaces are in reality liquid films, the pressure occurring from time to time during the glacier's movement down its unevenly inclined bed being most effective at these boundaries. Hence, molecular transpiration across them occurs, the crystal grains growing in size as the glacier descends, so materially indeed that while it is microscopic in the upper reaches, the 'firn', it may be as great as a yard or more at the snout of the glacier.

Of course Sir William emphasized the fact that the liquefaction of ice by pressure is rendered

possible by the very open structure of ice, as revealed by X-rays, which also accounts for the abnormal expansion (instead of contraction) of water on freezing. I would like to add that it is even yet rarely appreciated how immense is this volume change which occurs on the freezing of water, compared with the thermal expansion of either ice or water. That of ice has already been mentioned (0.00016), and that of water is not far different; between 7° and 8° C. it is 0.000053, between 10° and 11° it is 0.000091, and between 19° and 20° it is 0.00021, the average coefficient between 10° and 20° and also the actual coefficient at 15° being exactly 0.00016. For the interesting interval between the maximum density at 4° (or more accurately 3.945° C.) and 0° (without freezing) the total expansion of the water is only one ten-thousandth of its bulk. But when freezing occurs there is a sudden expansive leap of nearly one-tenth of the whole volume of water frozen. The 'water-flowers' (Tyndall's 'ice flowers') or negative ice-crystals, produced in a slab of lake-ice by passing through it the hot rays from an electric lantern, are particularly interesting as illustrating the foregoing fact most elegantly, for they always exhibit a vacuole about their centre, of about one-ninth of the water content in the whole star-like cavity. Sir William exhibited a film which had been taken at the Royal Institution of this phenomenon, and Fig. 3 reproduces one of the best of these six-rayed 'flowers' shown by the film.

At the recent meeting of the Snow and Ice Association already mentioned, Dr. C. H. Desch emphasized the necessity of distinguishing between plastic and viscous flow. He pointed out that the former means an immediate yield under constant stress, and quoted Ruskin's example of butter (plastic) and honey (viscous), as an excellent illustration of the difference. He also showed that no formula can be found for the flow of glacier ice because flow is here complicated by recrystallization. He also propounded the question as to whether, in the production of a crack in ice leading to the formation of a crevasse, the fracture occurred between the crystals or along the basal planes (glide planes) within the crystals. In this connexion, I well remember being present at the startling event of the birth of a crevasse. It occurred during a crossing of the Alphubeljoch from Saas-Fee to Zermatt, in company with Alessandro Corsi of Macugnaga. Suddenly there was an explosion like a rifle shot fired at one's feet, at which both of us leapt forwards (the rope being taut between us). On recovering our equanimity and looking down at the glacier surface, which at that spot had been unusually free from crevasses, we perceived a thin sinuous line of crack extending as far as we could see on

each side of us, which obviously, before our eyes, opened more and more, until as we left to resume our climb this new crevasse had widened to more than a couple of inches.

The chairman of the Association, Mr. Gerald Seligman, quoted recent work indicating that the individual crystal was the unit of glacier movement, and that the slightest differential movement of the crystal grains might well be one of the principal causes of glacier movement. It is to be hoped, and indeed expected, that confirmation or otherwise of this view, and the answer to Dr. Desch's question, may be forthcoming from the investigations now proceeding at the Jungfraujoch by Mr. Seligman and his collaborators.

In conclusion, it appears to me that practically every seriously suggested cause for the movement of glaciers that has ever been put forward does operate, each playing its part when the conditions are favourable to its operation, and several of them usually acting simultaneously. This opinion is not merely the result of an attempt to digest all the voluminous records of practical scientific work on glaciers, but of personal study commenced so long ago as the year 1891, materially assisted by careful examination of nearly two thousand photographs of ice and snow formations on glaciers and mountains, taken by me personally during more than thirty seasons spent in the Alps, besides visits to the Rocky Mountains and the Himalayas.

Cambridge Meeting of the British Association

General Arrangements

THE Sectional programmes for the Cambridge meeting of the British Association were outlined in NATURE of July 16; it remains to add some general remarks to the notice which appeared in these columns when the preliminary programme was issued last April.

The attendance promises to be large: it should well exceed the average figure (which, since, but excluding, the centenary meeting in 1931, is 2,274); and this despite the unusually early, and to some members rather disconcerting, date of the meeting, August 17–24. This was inevitable, in order to meet the convenience of the colleges which are so generously offering their accommodation to visitors. Those who remember the last Cambridge meeting, in 1904, may recall that it fell on exactly the same dates, for the same reason. Nevertheless, the attendance then was 2,789, a very high figure for those days, but one which the present officers (and especially the General Treasurer) would very gladly see surpassed this year. It may well be, however, that the indulgence of late-comers will have to be sought if there be not room for them all to hear Lord Rayleigh's presidential address on August 17. The same drawback supervened in 1904, when many were unavoidably excluded from the Corn Exchange in which Mr. Arthur (afterwards Lord) Balfour as president inaugurated the meeting. On the present occasion the address will be given in the Regal Cinema. There is more room there than in the Corn Exchange (and certainly those present will listen in conditions of greater comfort); but there may not be enough for all members. It has therefore been decided to number and reserve all seats and to issue tickets

early next month to members according to priority of their intimation to be present; any who receive tickets but who do not intend to use them will be besought to return them at once in order that they may be made available for other members. Consideration is being given to the desirability of relaying the address to another hall, a facility not available to the harassed officers in 1904.

The general arrangements are nearing completion, and an ample list of excursions and visits has already been issued to those who have intimated intention to attend. The full programme and timetable, together with the specially compiled scientific survey of the Cambridge district, will be sent out as usual some ten days in advance of the meeting.

In recent years, the Association has attempted to meet a widespread demand for more specific attention to the direct relations between science and its bearing upon the life of the community, by the simple method of indicating in the programme all communications which bear specifically on this question. There will, however, be presented to the Council and the General Committee important proposals to place the study and presentation of this aspect of the advancement of science in a more clearly defined position within the Association. It will be recommended that a Division for the social and international relations of science be established—the Council having already approved this step in principle, and has appointed a committee to consider and report upon the method of working the new Division. The inclusion of international relations is made with the more confidence because the interest of the American