XIII. *On some Physical Properties of Ice.* By John Tyndall, *F.R.S.*, *Professor of Natural Philosophy in the Royal Institution of Great Britain.*

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The observations upon Glaciers, to be recorded in a subsequent paper, led me to make some experiments upon the physical properties of ice, the results of which are, I hope, of sufficient interest to justify me in presenting them to the Royal Society.

§ I.

1. I availed myself of the fine sunny weather with which we were favoured last September and October, to examine the effects of solar heat upon ice. The experiments were made with the Wenham Lake and Norway ice. Slabs were formed of the substance, varying from one to several inches in thickness, and these were placed in the path of a beam rendered convergent by a double convex lens 4 inches in diameter, and possessing a focal distance of $10\frac{1}{2}$ inches. The slabs were usually so placed, that the focus of parallel rays fell within the ice. Having first found the position of the focus in air, the lens was screened; the ice was then placed in position, the screen was removed, and the effect was watched through an ordinary pocket lens.

2. A plate of ice an inch thick, with parallel sides, was first examined: on removing the screen the transparent mass was crossed by the sunbeams, and the path of the rays through it was instantly studded by a great number of little luminous spots, produced at the moment and resembling shining air-bubbles. When the beam was sent through the edge of the plate, so that it traversed a considerable thickness of the ice, the path of the beam could be traced by those brilliant spots, as it is by the floating motes in a dark room.

3. In lake ice the planes of freezing are easily recognized by the stratified appearance which the distribution of the air-bubbles gives to the mass. A cube was cut from a perfectly transparent portion of the ice, and the solar beam was sent through the cube in three rectangular directions successively. One was perpendicular to the plane of freezing, and the other two parallel to it. The bright bubbles were formed in the ice in all three cases.

4. When the surfaces perpendicular to the planes of freezing were examined by a lens, after exposure to the light, they were found to be cut up by innumerable small parallel fissures, with here and there minute spurs shooting from them, which gave the fissures, in some cases, a feathery appearance. When the portions of the ice traversed by the beam were examined parallel to the surface of freezing, a very beautiful appearance

revealed itself. Allowing the light from a window to fall upon the ice at a suitable incidence, the interior of the mass was found filled with little flower-shaped figures. Each flower had six petals, and at its centre was a bright spot, which shone with more than metallic brilliancy. *The petals were manifestly composed of water*, and were consequently dim, their visibility depending on the small difference of refrangibility between ice at 32° FAHR. and water at the same temperature.

5. For a long time I found the relation between the planes of these flowers and the planes of freezing perfectly constant. They were always parallel to each other. The development of the flowers was independent of the direction in which the beam traversed the ice. Hence, when an irregular mass of transparent ice was presented to me, by sending a sunbeam through it, I could tell in an instant the direction in which it had been frozen.

Allowing the beam to enter the edge of a plate of ice, and causing the latter to move at right angles to the beam, so that the radiant heat traversed different portions of the ice in succession, when the track of the beam was observed through an eye-glass, the ice, which a moment before was optically continuous, was instantly starred by those lustrous little bubbles, and around each of them the formation and growth of its associated flower could be distinctly observed.

6. The maximum effect was confined to a space of about an inch from the place at which the beam first struck the ice. In this space the absorption, which resolved the ice into liquid flowers, for the most part took place, but I have traced the effect to a depth of several inches in large blocks of ice.

7. At a distance, however, from the point of incidence, the spaces between the flowers became greater; and it was no uncommon thing to see flowers developed in planes a quarter of an inch apart, while no change whatever was observed in the ice between these planes.

8. The pieces of ice experimented on appeared to be quite homogeneous, and their transparency was very perfect. Why then did the substance yield at particular points? Were they really weak points of crystalline structure, or did the yielding depend upon the manner in which the calorific wave impinged upon the molecules of the body at these points? However these and other questions may be answered, the experiments have an important bearing upon the question of absorption. In ice the absorption of the rays which produce the flowers is fitful, and not continuous; and there is no reason to suppose that in other solids the case is not the same, though their constitution may not be such as to reveal it*.

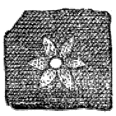
I have applied the term "bubbles" to the little bright disks in the middle of the flowers, simply because they resembled the little air-globules entrapped in the ice; but whether they contained air or not could only be decided by experiment.

* Notwithstanding the incomparable diathermaneity of the substance, M. KNOBLAUCH finds that when plates of rock-salt are thick enough, they always exhibit an elective absorption. Effects like those above described may possibly be the cause of this.

9. Pieces of ice were therefore prepared, through which the sunbeams were sent so as to develope the flowers in considerable quantity and magnitude. These pieces were then dipped into warm water contained in a glass vessel, and the effect, when the melting reached the bright spots, was carefully observed through a lens. *The moment a liquid connexion was established between them and the atmosphere, the apparent bubbles suddenly collapsed, and no trace of air rose to the surface of the warm water.*

10. This is the result which ought to be expected. The volume of water at 32° being less than that of ice at the same temperature, the formation of each flower ought to be attended with the formation of a vacuum, which disappears in the manner described when the ice surrounding it is melted.

Similar experiments were made with ice in which true air-bubbles were enclosed. When the melting liberated the air, the bubbles rose slowly through the liquid and floated for a time upon its surface.

11. Exposure for a second, or even less, to the action of the sun was sufficient to develope the flowers (4) in the ice. The first appearance of the central star of light was often accompanied by an audible clink, as if the substance had been suddenly ruptured. The edges of the petals were at the commencement definitely curved thus:  ; but when the action was permitted to continue, and sometimes even without this, when the sun was strong, the edges of the petals became serrated thus:  the beauty of the figure being thereby augmented.

Sometimes a number of elementary flowers grouped together to form a thickly-leaved cluster resembling a rose. Here and there also amid the flowers a liquid *hexagon* might be observed, but such were of rare occurrence.

12. The act of crystalline dissection, if I may use the term, thus performed by the solar beams, is manifestly determined by the manner in which the crystalline forces have arranged the molecules. By the abstraction of heat the molecules are enabled to build themselves together, by the introduction of heat this architecture is taken down. The perfect symmetry of the flowers, from which there is no deviation, argues a similar symmetry in the molecular architecture; and hence, as optical phenomena depend upon the molecular arrangement, we might pronounce with perfect certainty from the foregoing experiments, that ice is, what Sir DAVID BREWSTER long ago proved it to be, optically speaking, uniaxal, the axis being perpendicular to the surface of freezing.

§ II.

13. On the 25th of September, while examining a perfectly transparent piece of Norway ice, which had not been traversed by the condensed sunbeams, I found the interior of the mass crowded with parallel liquid disks, varying in diameter from the tenth to the hundredth of an inch. These disks were so thin, that when looked at in section they were reduced to the finest lines. They had the exact appearance of the

circular spots of oily scum which float on the surface of mutton broth, and in the pieces of ice first examined they always lay in the planes of freezing.

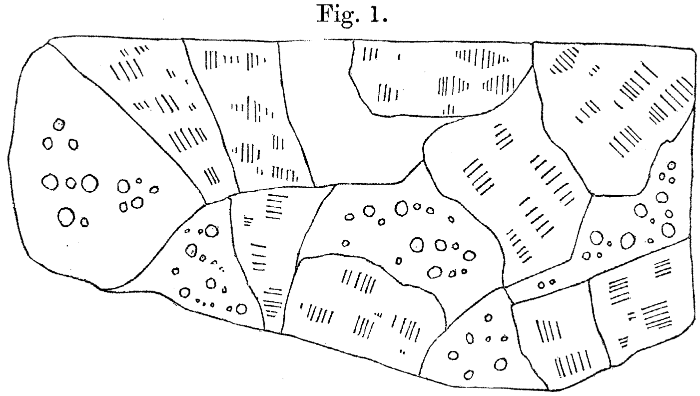
14. As time progressed this internal disintegration of the ice appeared to become more pronounced, so that some pieces of Norway ice examined in the middle of November, appeared to be reduced to a congeries of water-cells entangled in a skeleton of ice. The effect of this was rendered manifest to the hand on sawing a block of this ice, by the facility with which the saw went through it.

15. There seems to be no such thing as absolute homogeneity in nature. Change commences at distinct centres instead of being uniformly and continuously distributed, and in the most apparently homogeneous substance we should discover defects, if our means of observation were fine enough. The above observations show that some portions of a mass of ice melt more readily than others. The melting temperature of the substance is set down at 32° FAHR., but the absence of perfect homogeneity, whether from difference of crystalline texture or some other cause*, makes the melting temperature oscillate to a slight extent on both sides of the ordinary standard. Let this limit expressed in parts of a degree be t. Some parts of a block of ice will melt at a temperature of $32-t$, while others require a temperature of $32+t$: the consequence will be that such a block raised to the temperature of 32° will have some of its parts liquid, and others solid.

16. When a mass exhibiting the water-disks was examined by a concentrated sun-beam, the six leaved flowers before referred to *were always formed in the planes of the disks.*

17. In all my earlier experiments I found the rule to hold good, that both disks and flowers were developed in the planes of freezing, but I was subsequently surprised to find, in the self-same mass of ice, the disks lying in different planes. On examining such pieces I found them traversed by hazy surfaces of discontinuity, which divided the apparently continuous mass into irregular prismatic segments. When examined by allowing the red light of a fire to cross it, such ice had a beautiful appearance. The interior walls of the segments were thickly covered with rich liquid disks; in some cases the vision plunged unimpeded into the ice to a depth of several inches, while in others the prismatic segments were dotted with disks to their very centres. Fig. 1

Fig. 1.



* See Mr. FARADAY's Note on this subject at the end.

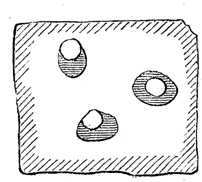
represents one of a number of cases of this kind which I had an opportunity of examining. The network of lines are the intersections of the bounding surfaces of the segments with the surface of the slab of ice: the short lines in each segment represent the sections of the disks; and it will be observed that while in each single segment their directions are alike, in no two segments is this the case. The flat rings denote that the disks, at these places, were parallel to the surface of the ice slab, while in all the other cases they were perpendicular to it.

18. I placed this slab on a table which could be caused to rotate, and bringing it into the path of a concentrated sunbeam, caused the beam to travel all round it. The little flowers started into existence with extreme suddenness and beauty. *In all cases the planes of the flowers were parallel to the planes of the disks.*

19. Hence the conclusion that the flowers are always parallel to the surface of freezing, must not go without qualification. There is no doubt that each of the fragments above referred to, possesses an optic axis perpendicular to the planes of the flowers developed in it; the directions of these axes being therefore as various as the planes aforesaid. How is this result brought about? Has the molecular structure of the ice been always what the last experiments show it to be? Sir DAVID BREWSTER'S observations are in opposition to this idea. Or can it be that the ice has changed, by a rearrangement of the constituent particles of each segment, this arrangement producing the surfaces of discontinuity by which the segments are bounded? At present we are confined to mere conjectures, but I hope the coming winter will enable me to investigate this highly interesting question.

§ III.

20. What has been already said will prepare us for the consideration of an associated class of phenomena of great physical interest. The larger masses of ice which I examined exhibited layers in which bubbles of air were collected in unusual quantity, marking, no doubt, the limits of successive acts of freezing. These bubbles were usually elongated. Between two such beds of bubbles a clear stratum of ice intervened; and a clear surface layer, which, from its appearance, seemed to have suffered more from external influences than the rest of the ice, was associated with each block. In this superficial portion I observed detached air-bubbles irregularly distributed, and associated with each vesicle of air, a bleb of water which had the appearance of a drop of clear oil within the solid. The adjacent figure will give a notion of these composite cavities: the unshaded circle represents the air-bubble, and the shaded space adjacent, the water.



21. When the quantity of water was sufficiently large, which was usually the case, on turning the ice round, the bubble shifted its position, rising always at the top of the bleb of water. Sometimes, however, the cell was very flat, and the air was then quite surrounded by the liquid. These composite cells often occurred in pellucid ice, which showed inwardly no other sign of disintegration.

This is manifestly the same phenomenon as that which struck M. AGASSIZ so forcibly during his earlier investigations on the glacier of the Aar. The same appearances have been described by the Brothers SCHLAGINTWEIT, and finally attention has been forcibly drawn to the subject in a recent paper by Mr. HUXLEY, published in the Philosophical Magazine*.

22. The only explanation of this phenomenon hitherto given, and adopted apparently without hesitation, is that of M. AGASSIZ and the Messrs. SCHLAGINTWEIT. These observers attribute the phenomenon to the diathermancy of the ice which permits the radiant heat to pass through the substance, to heat the bubbles of air, and cause them to melt the surrounding ice†.

The apparent simplicity of this explanation contributed to ensure its general acceptance; and yet I think a little reflection will show that the hypothesis, simple as it may appear, is attended with grave difficulties.

23. For the sake of distinctness I will here refer to a most interesting fact, observed first by M. AGASSIZ, and afterwards by the Messrs. SCHLAGINTWEIT. In the 'Système Glaciaire'‡ it is described in these words: "I ought also to mention a singular property of those air-bubbles, which at first struck us forcibly, but which has since received a very satisfactory explanation. When a fragment containing air-bubbles is exposed to the action of the sun, the bubbles augment insensibly. Soon, in proportion as they enlarge, a transparent drop shows itself at some point of the bubble. This drop, in enlarging, contributes, on its part, to the enlargement of the cavity, and following its progress a little, it finishes by predominating over the bubble of air. The latter then swims in the midst of a zone of water and tends incessantly to reach the most elevated point, at least if the flatness of the cavity does not hinder it."

24. The satisfactory explanation here spoken of is that already mentioned: let us now endeavour to follow the hypothesis to its consequences. Comparing equal weights of both substances, the specific heat of water being 1, that of air is 0·25. Hence to raise a pound of water one degree in temperature, a pound of air would have to lose four degrees.

25. Let us next compare equal volumes of the substances. The specific gravity of water being 1, that of air is $\frac{1}{770}$; hence a pound of air is 770 times the volume of a pound of water; and hence for a quantity of air to raise *its own volume* of water 1 degree, it must part with 770×4, or 3080 degrees of temperature.

* October, 1857.

† Il est évident pour quiconque a suivi le progrès de la physique moderne, que ce phénomène est dû uniquement à la diathermanéité de la glace (AGASSIZ, Système, page 157).

Das Wasser ist dadurch enstanden dass die Luft Wärmestrahlen absorbirte welche das Eis als diathermaner Körper durchliess (SCHLAGINTWEIT, Untersuchungen, S. 17).

‡ Page 168. The figures to which M. AGASSIZ refers in the note to this page seem to be correctly drawn, but his descriptive reference to them, though in part correct, is in part unintelligible to me. He uses the term *bulles* for the bubbles of air, and *gouttelettes* for the drops of water, and I believe the latter term is always restricted to a *liquid*. But if we restrict the term thus throughout the passage in question, there is no escape from Mr. HUXLEY'S conclusion, that M. AGASSIZ has taken the air-bubbles for drops of water, and the drops of water for air-bubbles.

26. Now the latent heat of water is 142°·6 FAHR., hence the quantity of heat required to melt a certain weight of ice is 142·6 times the quantity required to raise the same weight of water 1 degree in temperature; hence a measure of air, in order to reduce its own volume of ice to the liquid condition, must lose $3080 \times 142 \cdot 6$, or 439,208 degrees of temperature.

27. This then gives us an idea of the amount of heat which, according to the above hypothesis, is absorbed by the bubble and communicated to the ice during the time occupied in melting a quantity of the latter equal in volume to the bubble, which time is stated to be brief; that is to say, the quantity of heat supposed to be absorbed by the air would, if it had not been communicated to the ice, have been sufficient to raise the bubble itself to a temperature 160 times that of fused cast iron. Had air this power of absorption, it might be attended with inconvenient consequences to the denizens of the earth; for we should dwell at the bottom of an atmospheric ocean, the upper strata of which would effectually arrest all calorific radiation.

28. It is established by the experiments of DELAROCHE and MELLONI*, that a calorific beam, emerging from any medium which it has traversed for any distance, possesses, in an exalted degree, the power of passing through an additional length of the same substance. Absorption takes place, for the most part, in the portion of the medium first traversed by the rays. In the case of a plate of glass, for example, $17\frac{1}{2}$ per cent. of the heat proceeding from a lamp is absorbed in the first fifth of a millimetre; whereas, after the rays have passed through 6 millimetres of the substance, an additional distance of 2 millimetres absorbs less than 2 per cent. of the rays thus transmitted. Supposing the rays to have passed through a plate 25 millimetres, or an inch in thickness, there is no doubt that the heat emerging from such a plate would pass through a second layer of glass, 1 millimetre thick, without suffering any measureable absorption. For an incomparably stronger reason, the quantity of solar heat absorbed by a bubble of air at the earth's surface, after the rays have traversed the whole thickness of our atmosphere, and been sifted in their passage through it, must be wholly inappreciable.

29. To the sifting power of the atmosphere we must add, in the case of the glacier, the absorptive power of the ice. Some notion of this power, as compared with that of air, may be gathered from the following facts:—As regards the variation of the intensity of radiant heat with the distance, the law of inverse squares is capable of the strictest experimental verification in air, even when the source of heat is far below 212° FAHR. This implies that the absorption in the space of air through which the heat passes is too small to disturb the harmony of the law. Now a plate of ice, one-tenth of an inch thick, is absolutely impervious to heat emanating from a source, not only of 212°, but of 752° FAHR.; and is capable, moreover, of absorbing $99\frac{1}{2}$ per cent. of the calorific rays emitted by an incandescent platinum wire†. (La Thermochrose, p. 164.)

* La Thermochrose, p. 202.

† I can hardly forbear drawing attention here to the remarkable influence which the element *hydrogen* appears to exercise upon radiant heat, and the longer waves of light. Wherever hydrogen enters into a

Such, if I mistake not, are the properties of radiant heat which modern physics have revealed; and I think they render it evident that the hypothesis of M. AGASSIZ and the Messrs. SCHLAGINTWEIT was accepted without due regard to its consequences.

But as the sun does reach the lower strata of the atmosphere, it may be thought that we are protected from its effects by the radiation from the air neutralizing its absorption. The fact however is, that air may be heated to an intense degree without showing any measureable amount of radiation. The hot current from an Argand chimney produces, according to MELLONI, no sensible effect upon a delicate thermo-electric apparatus. Hence it is not because the air gets rid of its heat by radiation, but simply because its power of absorption is infinitely behind that supposed by the hypothesis of M. AGASSIZ and the Messrs. SCHLAGINTWEIT, that animal and vegetable existence at the earth's surface is possible.

When air-bubbles occurred in those portions of the ice where the liquid disks appeared, the associated water spread out on planes parallel to those of the disks, evidently in consequence of the freer yielding of the ice in these planes. Keeping this remark in view and comparing fig. 1 with fig. 10, plate 4 of M. AGASSIZ' Atlas, the resemblance of both phenomena will at once be perceived. The glacier ice, like the

compound, I think it may be predicted that it will destroy the longer undulations. For the present I will avoid speculation upon this subject, and confine myself to facts. If we examine the list of solid substances whose power to transmit radiant heat instantaneously have been examined by MELLONI, we find that those at the lower end of the list, that is, the most imperfectly diathermanous substances, all contain hydrogen. In no single case, where this element occurs, is the substance capable of transmitting rays from a source of 752° FAHR.; while in every case where it does not occur, the power of transmitting rays from this source is manifested in a greater or less degree. Amber, gum, citric acid, alum, sugar-candy, tartrate of potash and soda, are the substances which exercise this destructive agency upon the longer undulations; *ice* being the most non-diathermanous transparent body hitherto examined. Turning to MELLONI's list of liquids, the same fact reveals itself. There is a sudden fall in the power of transmission at the place where hydrogen enters the list. Protochloride of phosphorus transmits 62 per cent. of the rays incident upon it, but the next substance, hydrocarburet of chlorine, transmits only 37 per cent. From this point to the end of the Table the substances named all contain hydrogen, the list being closed by *distilled water*, which transmits only 11 per cent. of the calorific rays from an Argand lamp.

To the same element, I believe, is to be referred the difference between Sir W. HERSCHEL and SEEBECK as to the place of maximum heat in the solar spectrum. HERSCHEL found this place to be beyond the extreme red, but SEEBECK, with a prism of sulphuric acid, found it to be in the orange, while with a prism of water he found it in the yellow. MELLONI has shown that this is due to the destruction of the less refrangible rays by the two liquids, the sulphuric acid being regarded by him as acting in a manner analogous to water. In both the water and the sulphuric acid used by SEEBECK, I believe the hydrogen to be the agent which gives the observed character to the results. The *colour* of ice and water is also a necessary consequence of this hostility of the element hydrogen to the instantaneous passage of the longer undulations.

The mathematical theory of undulation is, perhaps, perfect, but the physics of the process, that is, the real affections of light and heat in their passage through bodies, are wholly unknown to us. Cases, therefore, like the foregoing, which single out a particular substance as exhibiting a special department towards light and heat, are, I think, of great value. Increased knowledge will probably enable us to connect these effects with the other properties of this substance, and thus establish physical relations which are now unknown to us.

Norway ice with which I experimented, is divided into segments by surfaces of discontinuity. The air- and water-cavities are represented as flattened, but, as in the lake ice, they seem flattened in all directions. M. AGASSIZ regards the flattening of the cavities as a certain proof that they have been squeezed flat by pressure; and he attributes the different directions of flattening to a power of independent motion possessed by each fragment. The perfect similarity, however, of the phenomena presented by the two kinds of ice must render us cautious in accepting an explanation which may apply to the one, but excludes the other.

§ IV.

30. But the question still remains, how are the water-chambers produced within the ice? Mr. HUXLEY throws out the suggestion, which our knowledge at the time of his observations rendered most probable, namely, that the water had never been frozen at all, but had preserved itself, like the liquid in the cavities of a Gruyère cheese, from the névé downwards.

31. One simple test will, I think, decide the question whether the liquid is or is not the product of melted ice. If it be, its volume must be less than that of the ice which produced it, and the bubble associated with the water *must be composed of rarefied air.* Hence, if on establishing a liquid connexion between this bubble and the atmosphere a diminution of volume be observed, this will indicate that the water has been produced by the melting of the ice.

32. From a block of Norway ice, containing such compound bubbles, I cut a prism, and immersing it in warm water, contained in a glass vessel, I carefully watched through the side of the vessel the effect of the melting upon the bubbles. *They invariably shrunk in volume at the moment the surrounding ice was melted*, and the diminished globule of air rose to the surface of the water. I then arranged matters so that the wall of the cavity might be melted away underneath, without permitting the bubble of air at the top to escape. At the moment the melting reached the cavity the air-bubble instantly collapsed to a sphere, possessing, in some cases, far less than the hundredth part of its original volume. The experiments were repeated with several distinct masses of ice, and always with the same result. I think, therefore, it may be regarded as certain that the liquid cells are the product of melted ice*.

33. Considering the manner in which ice imported into this country is protected from the solar rays, I think we must infer that in the specimens examined by me†, *the ice in contact with the bubble has been melted by heat which has been conducted through the substance without visible prejudice to its solidity.*

34. Paradoxical as this may appear, I think it is no more than might reasonably be expected from *à priori* considerations. The heat of a body is referred, at the present

* This of course refers to the lake ice examined as described. I venture to predict, however, that the same will be found true of the bubbles in glacier ice.

† And in those portions of glacier ice which are withdrawn from the direct action of the sun.

day, to a motion of its particles. When this motion reaches such an intensity as to liberate sufficiently the particles of a solid from their mutual attractions, the body passes into the liquid condition. Now as regards the amount of motion necessary to produce this liberty of liquidity, the particles at the surface of a mass of ice must be very differently circumstanced from those in the interior, which are influenced and controlled on every side by other particles. But if we suppose a cavity to exist within the mass, the particles bounding that cavity will be in a state resembling that of the particles at the surface; and by the removal of all opposing action on one side, the molecules may be liberated by a force which the surrounding mass has transmitted without prejudice to its solidity. Supposing, for example, that solidity is limited by molecular vibrations of a certain amplitude, those at the surface of the internal cavity may exceed this, while those between the cavity and the external surface of the ice may, by their reciprocal actions, be preserved within it, just as the terminal member of a series of elastic balls is detached by a force which has been transmitted by the other members of the series without visible separation *.

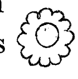
35. Where, however, experiment is within reach, we ought not to trust to speculation; and I was particularly anxious to obtain an unequivocal reply to the question whether an interior portion of a mass of ice could be melted by heat which had passed through the substance by the process of *conduction*. A piece of Norway ice, containing a great number of the liquid disks already described, and several cells of air and water, was enveloped in tinfoil and placed in a mixture of pounded ice and salt. A few minutes sufficed to freeze the disks to thin dusky circles, which appeared, in some cases, to be formed of concentric rings, and reminded me of the sections of certain agates. Looked at sideways, these disks were no thicker than a fine line. The water-cells were also frozen, and the associated air-bubbles were greatly diminished in size. I placed the mass of ice between me and a gas-light, and observed it through a lens: after some time the disks and water-cells showed signs of breaking up again. The rings of the disks disappeared; the contents seemed to aggregate so as to form larger liquid spots, and finally, some of them were reduced to clear transparent disks as before.

36. But an objection to this experiment is, that the ice may have been liquefied by the radiation from the lamp, and I have experiments to describe which will show the justice of this objection. A rectangular slab, 1 inch thick, 3 inches long and 2 wide, was therefore taken from a mass of Norway ice, in which the associated air- and water-cells were very distinct. I enveloped it in tinfoil and placed it in a freezing mixture. In about ten minutes the water-blebs were completely frozen within the mass. It was immediately placed in a dark room, where no radiant heat could possibly affect it, and examined every quarter of an hour. The dim frozen spots gradually broke up into little water parcels, and in two hours the water-blebs were perfectly restored in the centre of the slab of ice. When last examined, this plate was half an inch thick, and the drops of liquid were seen right at its centre.

* Of course I intend this to help the conception merely.

37. A second piece, similarly frozen and wrapped up in flannel, showed the same deportment. In an hour and a half the frozen water surrounding the air-bubbles was restored to its liquid condition. Hence no doubt can remain as to the possibility of effecting liquefaction in the interior of a mass of ice, by heat which has passed by *conduction* through the substance without melting it.

38. I have already referred to the formation of the liquid cavities observed by M. AGASSIZ, when glacier ice was exposed to the sun. The same effect may be produced by exposure to a glowing coal fire. On the 21st and 22nd of November I thus exposed plates of clear Wenham Lake ice, which contained some scattered air-bubbles. At first the bubbles were sharply rounded, and without any trace of water. Soon, however, those near the surface, on which the radiant heat fell, appeared encircled by a liquid ring, which expanded and finally became crimped at its border, as shown in the adjacent figure. The crimping became more pronounced as the action was permitted to continue*.



A second plate, crowded with bubbles, was held as near to the fire as the hand could bear. On withdrawing it, and examining it through a pocket lens, the appearance was perfectly beautiful. In many cases the bubbles appeared to be surrounded by a series of concentric rings, the outer ring surrounding all the others like a crimped frill.

39. I could not obtain these effects by placing the ice in contact with a plate of metal obscurely heated†, nor by the radiation from an obscure source. Indeed ice, as before remarked, is impervious to radiant heat from such a source‡. The rays from a common fire also are wholly absorbed near the surface upon which they strike, and hence the described internal liquefaction was confined to a thin layer close to this surface.

40. But not only does liquefaction occur in connexion with the bubbles, but the "flowers," already described as produced by the solar beams, start by hundreds into existence, when a slab of transparent ice is placed before a glowing coal fire. They, however, are also confined to a thin stratum of the substance close to the surface of incidence. In the experiments made in this way, the central stars of the flowers were often bounded by sinuous lines of great beauty.

41. The foregoing considerations show that liquefaction takes place at the surface of a mass of ice at a lower temperature than that required to liquefy the interior of the solid. At the surface the temperature 32° produces a vibration, to produce which, within the ice, would necessitate a temperature of $32°+x$; the increment x being the

* The blebs observed in glacier ice also exhibit this form: see fig. 8, plate 6, of the Atlas to the 'Système Glaciaire.' In fig. 13 we have also a close resemblance of the flower-shaped figures produced by radiant heat in lake ice.

† To develope water-cavities within ice a considerable time is necessary; more time indeed than was sufficient to melt the entire pieces of ice made use of in these *contact* experiments.

‡ Hence the soundness of the ice under the moraines; the sun's rays are converted into obscure heat by the overlying debris; this only affects a layer of infinitesimal depth, and cannot produce the disintegration of the deeper ice, as the direct sunbeams can.

additional temperature necessary to overcome the resistance to liquefaction, arising from the action of the molecules upon each other.

42. Now let us suppose two pieces of ice at 32°, with moistened surfaces, to be brought into contact with each other, *we thereby virtually transfer the touching portions of these pieces from the surface to the interior*, where $32+x$ is the melting temperature. Liquefaction will therefore be arrested at those surfaces. Before being brought together, the surfaces had the motion of liquidity, but the interior of the ice has not this motion; and as equilibrium will soon set in between the masses on each side of the liquid film and the film itself, the film will be reduced to a state of motion inconsistent with liquidity. *In other words, it becomes frozen and cements the two surfaces of ice between which it is enclosed**.

If I am right here, the importance of the physical principles involved are sufficiently manifest: if I am wrong, I hope I have so expressed myself as to render the detection of my error easy. Right or wrong, my aim has been to give as explicit utterance to my meaning as the subject will admit of.

§ V.

43. Mr. FARADAY'S experiments on the freezing together of pieces of ice at 32° FAHR., and all of those recounted in the paper published by Mr. HUXLEY and myself, find their explanation in the principles here laid down. The conversion of snow into névé, and of névé into glacier, is perhaps the grandest illustration of the same principle†. It has been, however, suggested to me that the sticking together of two pieces of ice may be an act of cohesion, similar to that which enables pieces of wetted glass, and other similar bodies, to stick together. This is not the case. There is no sliding motion possible to the ice. When contact is broken, it breaks with the snap due to the rupture of a solid. Glass and ice cannot be made to stick thus together, neither can glass and glass, nor alum and alum, nor nitre and nitre, at common temperatures. I have, moreover, placed pieces of ice together over night and found them in the morning so rigidly frozen together, that when I sought to separate them, the surface of fracture passed through one of them in preference to taking the surface of regelation. Many sagacious persons have also suggested to me that the ice transported to this country from Norway and the Wenham Lake may possibly retain a residue of its cold, sufficient to freeze a thin film enclosed between two pieces of the substance. But the facts already adverted to are a sufficient reply to this surmise. The ice experimented on cannot be regarded as a magazine of cold, *because parcels of liquid water exist within it.*

44. Nevertheless, as our present knowledge of the facility with which ice permits

* It is here implied that the contact of the moist surfaces must be so perfect, or in other words, the liquid film between them must be so thin, as to enable the molecules to act upon each other *across* it. The extreme tenuity of the film may be inferred from this. A thick plate of water within the ice would facilitate rather than retard liquefaction.

† On this point see the paper referred to at the commencement.

heat to pass through it by conduction is, as far as I know, absolutely null, I was glad to avail myself of an opportunity which presented itself of obtaining some approximate notion of this power. I owe this opportunity to the kindness of Mr. HARRISON, who had devised and perfected a machine for the manufacture of ice by the evaporation of ether. I first examined a mass of ice of the shape of the frustum of a cone. The diameter of the base was 10½ inches, of the top 7½ inches, and the length of the frustum was 2 feet. During the freezing of this mass a thermometer fixed on the ice showed a temperature of 8° below the zero of FAHR., or 40° of FAHR. below the freezing-point of water.

45. Fourteen hours after it had been frozen, the temperature of the mass, to a depth of 2 inches below the surface, was accurately 32° FAHR. At the heart of the frustum the temperature was 31¼°. The superficial portions of the frustum had been the coldest, and we see that in fourteen hours the ice of these portions rose forty degrees in temperature.

46. On the 24th of April, Mr. HARRISON had the kindness to place his excellent machine entirely at my disposition. The vessel which contained the water to be frozen was shaped like the inverted frustum of a cone, and was surrounded by a jacket, between which and the side of the frustum vaporized ether circulated; the whole being placed in a vessel of water. At 11 o'clock A.M., I placed a thermometer (A) in contact with the side of the vessel, and about 2 inches below the surface of the water. The machine commenced to act, an opalescence was soon observable on the sides, and after twenty minutes' action the thermometer was firmly imbedded in the ice. At 1 o'clock P.M., a second thermometer (B), placed at a distance of an inch from the side of the frustum, was also surrounded by ice. At 2^h 20^m P.M. a third thermometer (C) was placed at a distance of 1¾ inch from the side of the vessel, and at 5^h 30^m P.M. a fourth thermometer (D) was placed at a distance of 3 inches from the side. The observed temperatures of these thermometers at the times stated are given in the following Table:—

Time of observation.	A.	B.	C.	D.
h m				
11 A.M.	32°			
11 20	24			
12	15½			
1	11	26½°		
2	7½	21		
3	6	15¾	30°	
4	2¾	13	24	
5	½	9½	20	
8	− 3	+ 4	+11½	+22°

At 8^h 30^m P.M. the machine was stopped and the supply of ether was cut off. The mercurial columns began to rise gradually, and at 10 o'clock P.M. they were found to be as follows:—

A.	B.	C.	D.
27°	27°	27½°	28½°

The machine rested throughout the night, and at 8 o'clock on the morning of the 25th *all the thermometers stood at* 32°.

47. The machine was set going at 8 A.M. on the 25th, and continued working until 2 o'clock in the afternoon, its office now being, not to freeze, but to cool the ice already frozen. The thermometers were read off every quarter of an hour, but it is not necessary to record all the observations. The following are the temperatures noted at 8 and $11^h\ 30^m$ A.M. and at 2 P.M.:—

Time. h m	A.	B.	C.	D.
8	32°	32°	32°	32°
11 30	+ 1	11½	23	30½
2	−11	− 9	−3	− 1

48. At $2^h\ 45^m$ the machine was stopped and the supply of ether cut off. The upper surface of the ice was covered with 2 inches of hair-felt: the water surrounding the frustum and its jacket was at a temperature of 32°; the thermometers were read off every half-hour, but I will limit myself at present to a few observations. The temperatures at 2 o'clock were those stated at the close of the last Table.

Time of observation. h m	A.	B.	C.	D.
3 15 P.M.	+11°	+ 9°	+ 6°	+ 2°
4 15	18	17	14	11½
5 15	24	22½	20	18
8 15	28½	28½	27½	26½
11 15	31	30½	30	29½

On the 26th the following temperatures were observed:—

h m	A.	B.	C.	D.
9 A.M.	32°	31¾°	31½°	31¼°
1 30 P.M.	32	32	31¾	31½

At $1^h\ 30^m$ a hole was bored in the centre of the frustum to a depth of 5 inches, and in this another thermometer (E) was placed; its temperature at $3^h\ 30^m$ P.M. was 30½°. At 8 o'clock in the morning of the 27th the observed temperatures were the following:—

A.	B.	C.	D.	E.
32°	32°	32°	32°	32°

At the termination of the experiment the water surrounding the frustum was at a temperature of 36° FAHR.

49. These experiments show, that however bad the conducting power of ice, in comparison with other substances, may be, the assumption that blocks of it which have been preserved in this country through months of summer weather should still possess a magazine of cold beyond that due to a temperature of 32°, is wholly imcompatible with the physical character of the substance.

§ VI.

50. In a very interesting paper communicated to the British Association during its last meeting, Mr. JAMES THOMSON has explained the freezing together of two pieces of ice at 32° in the following manner:—"The two pieces of ice, on being pressed together at their point of contact, will at that place, in virtue of the pressure, be in part liquefied and reduced in temperature, and the cold evolved in their liquefaction will cause some of the liquid film intervening between the two masses to freeze." I am far from denying the operation under proper circumstances of the *vera causa* to which Mr. THOMSON refers, but I do not think it explains the facts. For freezing takes place without the intervention of any pressure by which Mr. THOMSON'S effect could sensibly come into play. It is not necessary to squeeze the pieces of ice together; one bit may be simply laid upon the other and they will still freeze. Other substances besides ice are also capable of being frozen to the ice. If a towel be folded round a piece of ice at 32°, they will freeze together. Flannel is still better. A piece of flannel wrapped round a piece of ice freezes to it sometimes so firmly that a strong tearing force is necessary to separate both. Cotton wool and hair may also be frozen to ice without the intervention of any pressure which could render Mr. THOMSON'S cause sensibly active*.

51. But there is a class of effects to the explanation of which the lowering of the freezing-point of water by pressure may, I think, be properly applied. The following statement is true of fifty experiments or more made with ice from various quarters. A cylinder of ice 2 inches high and an inch in diameter, was placed between two slabs of box-wood and submitted to a gradually increasing pressure. Looked at perpendicular to the axis, cloudy lines were seen drawing themselves across the cylinder; and when the latter was looked at obliquely, these lines were found to be the sections of dim hazy surfaces which traversed the cylinder, and gave it an appearance closely resembling that of a crystal of gypsum whose planes of cleavage had been forced out of optical contact by some external force.

Fig. 2 represents the cylinder looked at perpendicular to its axis, and fig. 3 the same cylinder where looked at obliquely.

Fig. 2.

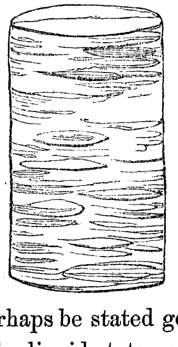
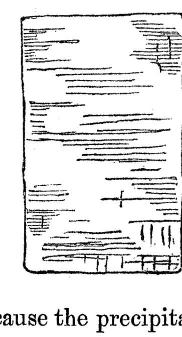


Fig. 3.



* It might perhaps be stated generally, that those substances which cause the precipitation of water from the gaseous to the liquid state, are also most influential in converting the liquid into the solid. "Hemp, wool, hair," are also the substances on which the so-called *ground-ice* is formed most readily. See ARAGO'S Report, *Annuaire pour l'an* 1833.

52. To ascertain whether the rupture of optical contact which these experiments disclosed was due to the intrusion of air between two separated surfaces of ice, a cylinder of ice, 2 inches long and 1 inch wide, was placed in a copper vessel containing ice-cold water. The ice-cylinder projected half an inch above the surface of the water. Placing the copper vessel on a slab of wood, and a second slab of wood upon the cylinder of ice, the whole was subjected to pressure. When the hazy surfaces were well developed in the portion of the ice above the water, the cylinder was removed and examined. The planes of rupture extended throughout the entire length of the cylinder, just the same as if it had been squeezed in free air.

Still the removal of the cylinder from its vessel might be attended with the intrusion of air into the fissures. I therefore placed a cylinder of ice, 2 inches long and 1 inch wide, in a stout vessel of glass, which was filled with ice-cold water. Squeezing the whole, as in the last experiment, the surfaces of discontinuity were seen forming *under the liquid* quite as distinctly as in air.

53. The surfaces are due to compression, and not to any tearing asunder of the mass by tension, and they are best developed where the pressure, within the limits of fracture, is a maximum. A cylindrical piece of ice, one of whose ends was not parallel to the other, was placed between slabs of wood and subjected to pressure. Fig. 4 shows the disposition of the experiment. The effect upon the ice-cylinder was that shown in fig. 5, the surfaces being developed along that side which had suffered the pressure.

Fig. 5.

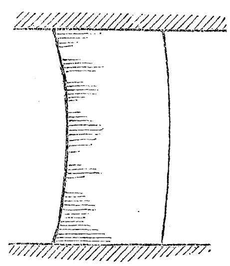
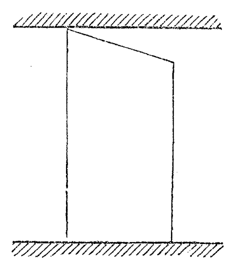


Fig. 4.



54. Sometimes the surfaces commence at the centre of the cylinder. A dim small spot is first observed, which, as the pressure continues, expands until it sometimes embraces the entire transverse section of the cylinder.

55. On examining these surfaces with a pocket-lens, they appeared to me to be composed of very minute water parcels, like what is produced upon a smooth cold surface by the act of breathing. Were they either vacuous plates, or plates filled with air, their aspect would, on optical grounds, be far more vivid than it really was.

56. A concave mirror was so disposed, that the diffused light of day was thrown full upon the cylinder while under pressure. Observing the expanding surfaces through a lens, they appeared in a state of intense commotion; this was probably due to the molecular tensions of the little water parcels. This motion followed closely on the edge of the surface as it advanced through the solid ice. Once or twice I observed the hazy surfaces pioneered through the mass by dim offshoots apparently liquid. They constituted a kind of negative crystallization, having the exact form of the crystalline spines and spurs produced by the congelation of water upon a surface of glass. I have no doubt, then, that these surfaces are produced by the liquefaction of the solid in planes perpendicular to the direction of pressure.

57. The surfaces were developed with great facility where they corresponded to the surfaces of freezing. Wherever the liquid disks before described were observed, the surfaces were always easily developed in the planes of the disks. By care I succeeded, in some cases, in producing similar effects in surfaces at right angles to the planes of the disks, but this was very difficult and uncertain.

I think the following new facts have been established in the foregoing paper:—

1. The interior of a mass of ice may be melted by *radiant heat* which has passed through exterior portions of the substance without melting them.

2. In the dissolution of the ice thus effected, the substance yields by the formation of liquid spaces, each possessing the shape of a flower with six petals, a small vacuum being formed at the centre of each flower.

3. These flowers are generally formed in planes parallel to the surface of freezing, but some of the specimens of ice examined were divided into prismatic segments by surfaces of discontinuity. Each distinct segment had its own system of flowers arranged in parallel planes, but the parallelism did not extend to the flowers of two distinct segments. This subject requires further investigation.

4. The appearance presented by masses of lake ice composed of these segments, resembles that of certain specimens of glacier ice in which the air- and water-cavities are flattened in different planes. Hence the explanation of the latter, which refers them to actions peculiar to the glacier, must be received with caution.

5. The explanation hitherto given of the water associated with the air-bubbles in glacier ice is untenable. In this paper the phenomenon is explained in accordance with the dynamical theory of heat. It is sought to be shown that, owing to the mutual action of the ice-molecules, a quantity of heat which has been *conducted* through the substance without prejudice to its solidity may liberate the molecules which bound an internal cavity, and thus produce water-cells in association with the bubbles of air.

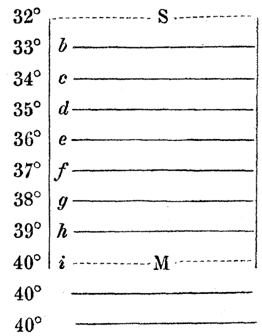
6. The converse of this takes place where two moist surfaces of ice at 32° Fahr. are brought into contact. Superficial portions are thus virtually rendered central; liquefaction is checked, the film of moisture on the surfaces in contact congeals, and the pieces of ice freeze together. To this process the term *regelation* has been applied.

7. By the application of pressure parallel surfaces of discontinuity are formed in lake and river ice perpendicular to the directions in which the pressure is exerted; thus giving the substance the appearance of selenite, in which the planes of cleavage are not in optical contact. The discontinuity consists in the liquefaction of the ice in these planes by the pressure. Such surfaces are formed with great facility parallel to the planes in which the liquid flowers are formed by radiant heat, while it is very difficult to produce them perpendicular to these planes. Thus, whether we apply heat or pressure, lake ice melts with peculiar facility in certain directions.

Note from Mr. Faraday.

My dear Tyndall,

Have the following remarks, made in reference to the irregular fusibility of ice, to which you drew my attention, any interest to you, or by an occasional bearing on such cases, any value in themselves? Deal with them as you like.



Imagine a portion of the water of a lake about to freeze, the surface S being in contact with an atmosphere considerably below 32°, the previous action of which has been to lower the temperature of the whole mass of water, so that the portion below the line M is at 40°, or the maximum density, and the part above at progressive temperatures from 40° upwards to 32°; each stratum keeping its place by its relative specific gravity to the rest, and having therefore, in that respect, no tendency to form currents either upwards or downwards. Now generally, if the surface became ice, the water below would go on freezing by the cold conducted downwards through the ice; but the successive series of temperatures from 32° to 40° would always exist in a layer of water contained between the ice and the dense water at 40° below M. If the water were *pure*, no action of the cold would tend to change the places of the particles of the water or cause currents; because the lower the cold descended, the more firmly would any given particle tend to retain its place above those beneath it: a particle at *e*, for instance, at 36° Fahr., would, when the cold had frozen what was above it, be cooled sooner and more than any of the particles beneath, and so always retain its upper place as respects them.

But now, suppose the water to contain a trace of saline matters in solution. As the water at 32° froze, either at the surface or against the bottom of the previously-formed ice, these salts would be expelled; for the ice first formed (and that *always* formed, if the proper care be taken to displace the excluded salts) is perfectly free from them, and pure. The salts so excluded would pass into the layer of water beneath, and there produce two effects: they would make that layer of greater specific gravity than before, and so give it a tendency to sink into the warmer under layer; but they would also make it require a lower temperature than 32° for congelation; this it would acquire from the cold ice above, and by that it would become lighter and float, tending to remain uppermost; for it has already been shown that the diminution of temperature below 32° in sea water and solution of salts, is accompanied by the same enlargement of bulk as between 32° and 40° with pure water. The stratum of water, therefore, below the ice, would not of necessity sink because it contained a little more salt than the stratum immediately below it; and *certainly would not* if the increase of gravity conferred by the salts was less than the decrease by lowering of temperature. An approximation of the strata between the freezing place and the layer at 40° would occur, *i. e.* the distance between these temperatures would be less, but the water particles would keep their respective places.

When water freezes, it does not appear that this process is continuous, for many of the characters of the ice seem to show that it is intermittent; *i. e.* either a film of ice is formed, and then the process stops until the heat evolved by solidification has been conducted away upwards, and the next stratum of water has been sufficiently cooled to freeze in turn; or else the freezing being, so to speak, continuous, still is not continued at the same constant rate, but, as it were, by intermittent pulsations. Now it may well be, when a layer next the previously-formed ice, and containing an undue proportion of salts, has been cooled down to its required temperature for freezing (which would be below 32°), that on freezing, the congelation will pervade at once a certain thickness of the water, excluding the salts from the larger portion of ice formed, but including them as a weak solution within its interstices. The next increment of cold conducted from the ice above would freeze up these salts in the ice containing them, at the same time that a layer of pure ice was formed beneath it. Thus a layer of ice fusible at a lower temperature than the ice either above or below it might be produced; and by a repetition of the process many such layers might be formed.

It does not follow necessarily that the layers would be perfectly exact in their disposition. Very slight circumstances tending to disturb the regularity of the water-molecules would be sufficient, probably, to disturb the layers more or less. Ice contains *no* air, and the exclusion of a minute bubble of air from the water in the act of freezing might disturb the direction and progress of the congelation, and cause accumulation of the extra saline liquid in one spot rather than another: so might the tendency to the formation of little currents, either arising from the separation of the saline water from the forming ice, or from the elevation of temperature in different degrees at those places where the congelation was going on at different rates.

The effect would not depend upon the quantity of salts contained in the freezing water, though its degree would. The proportion of salts necessary to be added to pure water to lower its freezing-point 1° FAHR. may be very sensible to chemical tests, but the proportion required to make the difference $\frac{1}{100}$th or $\frac{1}{1000}$th of a degree would be far less: and if we suppose that only $\frac{1}{20}$th of a piece of ice is brought into the condition of melting before the rest of the mass, and that the salts in that proportion were originally in the *whole* of the water, then its quantity there may be so small as to escape detection except by very careful analysis. However, it would be desirable to examine the water chemically which is produced by ice distinguished by having in its interior much, that liquefies before the rest.

It is easy to make ice perfectly free from air, and, as I believe, from salts, by a process I formerly described. It would be interesting to see if such ice had within it portions melting at a lower temperature than the general mass. I think it ought not.

Ever truly yours,

M. FARADAY.

Royal Institution,
9th December, 1857.