

IV. *On new properties of heat, as exhibited in its propagation along plates of glass.* By David Brewster, LL. D. F. R. S. Lond. and Edin. In a Letter addressed to the Right Hon. Sir Joseph Banks, Bart. G. C. B. P. R. S.

Read January 11, 1816.

DEAR SIR,

IN two papers published in the Transactions of the Royal Society,* I have given some account of the action of heat in enabling glass to arrange a beam of light, into two oppositely polarised pencils, and I have shown that unannealed glass, in the form of Prince RUPERT'S drops, possesses distinct optical axes, and acts upon light like all regularly crystallized bodies.

My attention was sometime ago recalled to this subject, in consequence of having discovered that reflection from all the metals, and total reflection from the second surfaces of transparent bodies, produced the same effect as crystallized plates, in separating a beam of polarised light into its complementary tints. I was thus led to believe, that the existence of two oppositely polarised pencils, and the production of the complementary colours, were concomitant effects, and I prepared to examine the truth of this supposition in the case of heated glass. In my early experiments on this subject, I had not observed these colours, as I was not then in the possession of a mode of detecting them, when they formed the lower tints of the

* See Phil. Trans. 1814, p. 436, and 1815, p. 1.

first order of NEWTON'S scale (*Opticks*, B. II. Part II.); but I have since discovered a method of rendering them in every case visible, by their effects in modifying the colour of a standard plate of sulphate of lime.

The results of these experiments, while they confirm the supposition which I had made, have also led to the discovery of many singular phenomena, which constitute a new branch of physics, analogous in its general character to the sciences of magnetism and electricity. The curious properties of light and heat, which are explained in the following paper, and the new views which are unfolded respecting the structure of crystallized bodies, will I trust, attract the notice of the chemist, the mineralogist, and the natural philosopher; while the variety and splendour of the phenomena which it embraces, will recommend it to the attention of those, who value scientific researches merely as subjects of exhibition or amusement.

Sect. I. *On the transient effects exhibited during the propagation of heat along plates of glass, or during its communication from glass to surrounding bodies.*

PROPOSITION I.

When heat is propagated along a plate of glass, its progress is marked by the communication of a crystalline structure, which changes its character with the temperature, and which vanishes when the heat is uniformly diffused over the plate.

If we lay the edge of a plate of glass upon a bar of red hot iron placed horizontally, and transmit through it a ray of light polarised in a plane inclined 45° to the horizon, the light will be depolarised in various degrees in different parts of the glass. When the temperature is made uniform, the glass plate loses its property of depolarisation. In order to prove that an

inequality of temperature is necessary to the development of this structure, I held a small plate of glass in a pair of hot pincers with globular ends. It instantly acquired the depolarising structure, and lost it when the diffusion of the heat became uniform. I then cooled the glass, and held it a second time in the same pincers, which were now much colder than before: the depolarising structure was again communicated to it as formerly.

The same result was obtained when 12 plates of glass were placed upon a bar of red hot iron.

PROPOSITION II.

When a plate of glass is brought to an uniform temperature considerably above that of the atmosphere, the communication of its heat to the surrounding air, or to other contiguous bodies colder than itself, is marked by the production of a crystalline structure, similar to that which is described under the preceding proposition.

I took three plates of thick mirror glass, and brought them to an uniform temperature by immersion in boiling water. In this state they exercised no action upon polarised light; but when their edges were placed upon a mass of cold iron, the inequality of temperature, occasioned by the abstraction of their heat, produced a crystalline structure at the very edge of the plates, which polarised a bluish white tint of the first order. At a greater distance from the edges, the plates depolarised a lower* tint in NEWTON'S scale. When the plates

* One tint is said to be *higher* than another, when it belongs to a *higher* order, or is at a greater distance from the black, or the commencement of the scale. This explanation is rendered necessary, in consequence of M. BIOT'S having used this term in the opposite sense.

are held in the air, the same effect is produced, but in a less degree. See PROP. XIV.

PROPOSITION III.

When heat is propagated along a plate of glass, its particles assume such an arrangement that it exhibits distinct neutral and depolarising axes, like all doubly refracting crystals, the neutral axes being parallel and perpendicular to the direction in which the heat is propagated.

When a ray of light polarised in a plane inclined 45° to the horizon, is transmitted through a glass plate DCEF Fig. 1. (Pl. II.) placed upon a piece of hot iron AB, lying horizontally, it is completely depolarised; but when the plane of primitive polarisation is parallel or perpendicular to the horizon, no change is produced upon the polarised ray, an intermediate effect being exhibited in intermediate positions, as in regularly crystallized bodies. Hence DE is the neutral axis, and DF the depolarising axis of the plate.

PROPOSITION IV.

When the depolarising structure is communicated to glass by heat in the manner already described, the glass acquires the property of arranging polarised light into its complementary colours.

The apparatus being arranged as in Prop. III, let the light transmitted through the glass DCEF be analysed by a prism of calcareous spar, or by reflection at the polarising angle from a plate of black glass, having a motion of rotation round the polarised ray. When the plane of reflection from the black glass is perpendicular to the plane of primitive polarisation, the whole surface of the glass plate will be covered with beautiful and highly coloured fringes parallel to CD, as

represented in Fig. 2. (Pl. II.); and when the plane of reflection is moved round 90° from this position, the surface of the glass will be covered with the complementary fringes, the colours gradually passing from the one state into the other during the rotatory motion of the black glass, in the same manner as in crystallized bodies.

The nature and intensity of the tints are represented by the following formulæ, which are the same as those which M. BIOT found for crystallized bodies.*

$$P = O + E \cos.^2 2 a.$$

$$\Pi = E \sin.^2 2 a.$$

In these formulæ P represents the ordinary pencil, and Π the extraordinary pencil: O is the coloured tint which preserves its primitive polarisation, and is not acted upon by the crystallized glass: E is the complementary tint which has lost its primitive polarisation by the action of the glass being polarised in an angle equal to $2 a$: and a is the azimuthal angle which the axis of the plate forms with the plane of primitive polarisation.

PROPOSITION V.

The coloured fringes mentioned in the preceding Proposition, and represented in Fig. 2. consist of six different sets, two exterior, two interior, and two terminal sets. The exterior sets occupy the edges, the interior sets the middle, and the terminal sets the extremities of the glass plate, and each set is separated from its adjacent set by a deep black fringe.

These different sets of fringes are represented in Fig. 2. (Pl. II.) where CDEF is the glass plate, and CD the edge of it which rests upon the hot iron. The first *exterior* or *lateral*

* See BIOT'S *Recherches sur la polarisation de la lumiere*, p. 21.

set, is comprehended between CD the edge of the plate and the black fringe MN, and the 2d exterior or lateral set between the opposite edge of the plate FE and another black fringe OP.

The first *interior* or *central* set lies between MN and *a b*, a line equidistant from the two black fringes, and the 2d interior or central set between OP and the same line *a b*. The first exterior set contains a greater number of fringes than the second exterior set, but in the latter they have a greater breadth; and in both these sets the fringes diminish in breadth, as they recede from the black spaces MN, OP. The *terminal* fringes appear at the extremities MO, NP of the plate.* They are separated from the central fringes by a faint black space, which becomes lighter as the tints increase; and from the lateral fringes by a *diagonal* black space bisecting the angles E, C, D, F. As the tints increase in number, the terminal fringes suffer particular changes, which will be described in the second part of this paper.

When the glass plate extends far beyond the heated iron, the terminal fringes are not produced.

PROPOSITION VI.

To explain the successive developement and subsequent extinction of the fringes during the propagation of the heat along the glass plate.

When the plate of glass CDEF, Fig. 2. (Pl. II.) is set upon the hot iron, a fringe or wave of a pale white colour instantly appears along the line CD, and gradually advances upon the

* The terminal fringes are not shown in this figure; but they are represented in Figs. 3, 4, 8, (Pl. II.) 20 and 21, (Pl. III.)

glass, driving as it were before it a dark and undefined wave. Nearly at the same instant a similar but fainter white wave advances from the upper edge EF, driving before it a similar undefined dark wave; and at no perceptible interval of time, another white fringe appears in a very diluted state about the centre *a b*, advancing towards the edges CD and EF. The waves of white light, which have their origin at the edges of the plate, and those which advance to meet them from the middle, have the effect of condensing the undefined dark waves into two black fringes MN, OP. A faint *yellow* wave next appears at CD, encroaching gradually upon the white one, and is followed by *orange* and *red* tints, completing the first order of colours in NEWTON'S scale. The colours of the second order next advance in succession, and the same thing happens with all the superior orders, so that *three*, *four*, and sometimes even *nine* or *ten* orders of colours are distinctly seen between MN and CD. When the *green* colour of the second order appears at CD, a wave of *yellow* of the first order is seen at FE advancing upon the plate, and is followed by tints of *orange*, *red*, *purple*, &c. till several orders are distinctly visible between FE and OP; and nearly at the same time another yellow wave develops itself at *a b*, and gradually encroaches on both sides upon the white fringe, but never reaches MN or OP. The *yellow* at *a b* next becomes *orange*, *pink*, *purple*, *blue*, *green*, &c. Each of these colours advances towards MN and OP, but never covers entirely the preceding colour, so that new fringes, sometimes to the number of six or eight, are thus formed between the black spaces.

The *terminal* fringes are developed at the same time, and nearly in a similar manner.

As the heat of the iron becomes more uniformly diffused over the plate of glass, the fringes between MN and CD diminish rapidly in number, and pass off at CD, those which remain always increasing in magnitude. The same effect takes place at EF, but more slowly, so that there is a particular time when the fringes between EF and OP are equally numerous as those between CD and MN. The two interior sets diminish and disappear in a similar manner, the part AB re-exhibiting all its former colours in an inverse order. Nothing is now seen but the white and black fringes, which gradually die away, and at last disappear when the temperature of the glass becomes uniform.

PROPOSITION VII.

The colours of the fringes in all the six sets ascend in NEWTON'S scale as they recede from the black spaces MN, OP, the fringes adjacent to these spaces being composed of the colours of the first order.

The truth contained in this proposition might have been safely deduced from a comparison of the tints with those in NEWTON'S scale, or with the table of colours which I have found in the rings exhibited by topaz when exposed to a polarised ray.* In order, however, to obtain a more convincing proof, I took a plate of sulphate of lime, which polarised a bright blue of the second order, and combined it with the plate of glass CDEF. When the axis of the sulphate of lime was parallel to the axis CD, the *blue* of the second fringe below MN was converted into *black*, a tint due to the difference of their actions; but when its axis was at right angles to CD, the same

* See *Phil. Trans.* 1814, p. 204.

blue fringe was converted into a *yellowish green*, a tint due to the sum of their actions. Hence it follows, that the blue in the second fringe below MN is a blue of the second order. Similar results were obtained by combining the sulphate of lime with the parts of the glass which produced the other sets of fringes.

Another proof of the proposition was obtained in the following manner. I took two plates of thick glass, and having placed them on a hot iron, as before, I waited till all the fringes had disappeared except the white of the first order. When one of the plates was lifted vertically, so that the portion of the glass CDN_M was opposite to *a b*, the two white fringes produced a black tint. When the same plate was depressed till *a b* of the one plate was opposite to CD of the other, the white fringe above CD was also converted into black. This black, however, was not so deep as before, as the white in the exterior fringe is brighter than in the interior one. In the first case, this superiority was compensated by the cooling of the glass at CD, in consequence of its being lifted from the hot iron, whereas in the second case, the cooling had not affected the interior part *a b*. When, on the contrary, the one plate was held in such a position that its fringes were at right angles to those of the other, as shown in Fig. 3, (Pl. II.) the white of the exterior fringes of the one plate combined with the white of the exterior fringes of the other, produced black. The white of the interior fringes of the one plate, when combined with those of the other plate, produced black, and the white of the interior fringes of the one plate, when combined with the white of the exterior fringes of the other, produced a brighter white.

The result of these combinations is the production of a dark cross, as represented in Fig. 3. (Pl. II.) This cross is extremely regular and beautiful when the two plates have the same breadth, polarise the same tints, and have their exterior fringes of the same magnitude at both edges. When some of these circumstances are varied, the cross changes its form in a manner which can easily be ascertained from a previous examination of the separate fringes; but, when the one plate polarises higher tints than the other, the cross is no longer produced. The fringes of the plate which polarises the highest tint, are bent from their rectilinear direction, as represented in Fig. 4. (Pl. II.) As the figures exhibited at the intersection of two plates can always be determined, *a priori*, from a knowledge of the fringes which each plate produces separately, so the nature of the separate fringes, and the rate at which the tints change, may be easily predicted from the figures which are exhibited at the place of intersection. When the tints polarised by the two plates are numerous and brilliant, the intersectional figures are singularly beautiful.

PROPOSITION VIII.

The parts of the plate of glass which exhibit the two exterior sets of fringes, have the same structure as that class of doubly refracting crystals, including sulphate of lime, quartz, &c. in which the extraordinary ray is attracted to the axis, while the parts of the glass, which exhibit the two interior and the terminal sets, have the same structure as the other class of doubly refracting crystals, including calcareous spar, beryl, &c. in which the deviation of the extraordinary ray from the axis, is produced by a repulsive force. The portions between these which produce the black spaces, have an intermediate structure, like those portions of muriate of soda, fluor spar, and the diamond, which are destitute of the property of double refraction.*

In order to establish this singular result, I combined a standard plate of sulphate of lime which polarised a bright blue of the second order, with the different parts of the glass which produced the six sets of fringes. When the axis of the plate of sulphate of lime was parallel to the fringes, or to CD, the blue of the second fringe in the first exterior set below MN, and the blue of the second exterior fringe above OP, were converted into *black*, but when the axis of the sulphate of lime was perpendicular to CD, the blue of the same fringes was converted into *yellowish green*. On the contrary, when the axis of the plate of sulphate of lime was perpendicular to CD, the blue of the second fringe of the first interior set above MN, and the blue of the second fringe of the second interior

* See LAPLACE'S valuable Memoir, *Sur la loi de la refraction extraordinaire dans les cristaux diaphanes*, Mem. de L'Institut. 1809.

set below OP, were converted into *black*; but when the axis of the sulphate of lime was parallel to CD, the *blue* of the same fringes was converted into a *yellowish green*. Hence it follows, that the axis of the parts of the glass which form the exterior sets of fringes, is at right angles to the axis of the parts which form the interior sets. The same result is deducible from the second experiment in Prop. VII. Since, therefore, the same effects as those which we have described, are produced by combining crystallized plates taken from the two classes of doubly refracting crystals, as has been ably proved by M. BIOT,* we may consider the truths stated in the Proposition as completely established.

Cor. It follows from this Proposition, that a single plate of glass, crystallized by the propagation of heat, and exposed to a polarised ray, exhibits the same variety of phenomena as all the crystals in the mineral kingdom. We have already seen, that it possesses the structure of all the three classes of doubly refracting crystals. But the individual crystals which compose these classes, are distinguished from each other by the magnitude of their polarising forces, and the same variety is exhibited in the polarising forces of the glass, the parts which are adjacent to CD, *ab*, and FE, having the structure which gives the greatest polarising force, and the parts adjacent to OP, MN, the structure which gives the least polarising force.

* See M. BIOT's *Mémoire sur la découverte d'une propriété nouvelle dont jouissent les forces polarisantes de certains cristaux*. Mém. de l'Institut, 1814.

PROPOSITION IX.

When the temperature of the source of heat remains the same, the thicknesses of the glass, whether one or more plates are used, which polarise any particular colour, under a perpendicular incidence, are proportional to the thicknesses of thin uncrystallized plates, which would reflect the same colour in the phenomenon of coloured rings.

M. BIOT has shown with much ingenuity, that the thicknesses of sulphate of lime, rock crystal, and calcareous spar, which polarise any particular colour, are proportional to the thicknesses of the uncrystallized plates which reflect that colour:* and there was reason to believe that the same law would regulate the phenomena exhibited by heated glass.

I took several plates of glass of various thicknesses, from the thinnest German crown glass, about $\frac{1}{25}$ th of an inch thick, to plate glass $\frac{1}{4}$ of an inch thick, and, having placed them all upon a piece of red hot iron, I found that the number of orders of colours which were developed, was nearly related to the thickness of the glass. As these plates, however, had not the same chemical composition, I employed several pieces of thick mirror glass cut out of the same plate. I placed one of these by itself on the hot iron, and marked the particular tint which it polarised in the first order of NEWTON'S scale.

All the rest of the plates having been placed on the hot iron at the same time with the first, I took each of them in succession, and joined it to the first plate; the tints which were thus produced, ascended in the order of colours as the

* See BIOT'S *Recherches sur la polarisation de la lumière*, p. 53.

number of plates was increased, and were always such as belonged to a thickness taken in proportion to the number in the third column of NEWTON'S scale.

When one plate, for example, polarised at *ab*, a yellow of the first order, two plates gave an *indigo* of the second order, three a *red* of the second order, four a *green* of the third order, five a *bluish red* of the third order, and six a *yellowish green* of the fourth order. Now the numbers representing these tints in NEWTON'S scale, are nearly 4, 8, 12, 16, 20, 24, and the corresponding thicknesses are 1, 2, 3, 4, 5, 6. A variety of other experiments were made with the same result.

PROPOSITION X.

If a number of glass plates of the same form and of the same chemical composition, but of various thicknesses, are placed upon a hot iron, then if two or more of them are combined symmetrically, that is with their edges CD coincident, the colour polarised in any part will be the same as that which would have been polarised by a single plate having a thickness equal to the sum of the thicknesses of the plates; but if the plates are placed transversely, or with their edges CD at right angles to each other, the colour polarised at those parts of the glass, which are similarly situated with regard to the black spaces, is the same as that which would have been polarised by a single plate, whose thickness is equal to the difference of the thicknesses of the two transverse plates or systems of plates.

I took two plates of mirror glass that had different thicknesses, but nearly the same colour, and having cut them into equal rectangular pieces, I found that three of the one had the same thickness as *five* of the other.

These two parcels of plates were then placed upon the hot iron, and the one parcel exhibited the same tints as the other, both in the exterior and interior fringes.

In order to prove the second part of the proposition, I took three parcels, one of *two* plates, another of *four* plates, and a third of *six* plates, all of them having been cut out of the same mirror. I then placed the different parcels upon the hot iron, and when the colours were perfectly developed, I held the system of *four* plates in a position transverse to the system of *six* plates as shown in Fig. 3. (Pl. II.) A broad fringe of blue light of the second order appeared at the intersection of the central lines *a b*, *a' b'*. The very same colour was polarised by the system of two plates, whose united thickness was equal to the difference of the thickness of the transverse parcels. See Prop. XV.

PROPOSITION XI.

The number and form of the plates of glass remaining the same, the tints which are polarised at the central line a b, and at the edges CD, FE, Fig. 2, (Pl. II.) ascend in NEWTON'S scale as the temperature of the source of heat is increased.

I took a thick plate of mirror glass 6,9 inches long, 2,27 inches high, and 0,163 thick, and having placed it upon a heated iron, which just appeared red hot in the dark, I found that it polarised the *green* of the second order in the *first* exterior set of fringes, and the greater part of the *white* of the first order in the second exterior set of fringes. When the heat was more intense, the same plate polarised the *green* of the third order in the *first* exterior set of fringes.

When 15 plates of mirror glass were placed upon the top

of a tin vessel enclosing water at a temperature of 190° , they polarised a *green* of the second order. The united thickness of these plates was 1.7 of an inch.

When the heat of my hand was communicated to 11 plates of crown glass, they polarised the blue of the first order, and exhibited distinctly the two black spaces. The temperature of the room during these experiments was 64° . Even one plate of crown glass about 0.28 of an inch thick, exhibits the black spaces and the bluish white fringes by the heat of the hand.

The preceding results are neither sufficiently numerous nor accurate to enable me to determine the relation between the thickness corresponding to the highest tint, and the temperature of the source of heat. An apparatus, however, is preparing for me, by which this point will be easily ascertained by obtaining various temperatures from heated oil or mercury. See Sect. II.

PROPOSITION XII.

The number and form of the plates of glass, and the temperature of the source of heat remaining the same, the magnitude of the fringes of the first exterior set depend upon the law of the decrease of temperature in that part of the glass which produces them. The highest order of colours is always developed where the temperature is a maximum, and the tints descend in the scale as the temperature diminishes.

Let CDEF, Fig. 5. (Pl. II.) be a plate of glass, MN one of the black spaces, and the portion CDN, that which produces the first exterior set of fringes.

The temperatures at the points B, K, G may be represented by the ordinates BD, GH, KL, of the curve TLHD. The

highest tint is polarised at B where the temperature BD is greatest. A lower tint in the scale appears at G, depending on the temperature GH, and a still lower tint at K where the temperature is reduced to KL. As the temperature of the iron RS diminishes, and the diffusion of the heat over the glass becomes more uniform, the temperature at B will be changed to B *d*, the temperature at G to G *h*, and the temperature at K to K *l*. So that the curve will now have the form *m l h d*. When this happens, the fringes grow broader and diminish in number.

When the diffusion of the heat is uniform, the temperatures and consequently the ordinates will every where be equal, and the curve will change into a straight line, in which case, the fringes completely disappear. When the plate CDEF is lifted from the iron, it begins to cool at CD. The fringes pass off at the edge CD, exhibiting a broad fringe of the same tint. The differences of the temperatures now vary less rapidly, and the line TLHD, becomes a curve of contrary flexure, such as TLHVW or TLHX, when the cooling has made greater progress.

I have not been able to ascertain exactly the relation between the thickness corresponding to the polarised tints at different distances from the source of heat, and the temperature of the glass at the same points; but by assuming the most probable law of the decrease of temperature, and comparing it with the magnitude of the fringes, there is reason to believe, that the thicknesses are nearly proportional to the temperature.

The tints polarised at different parts of the glass plate (a section of which is shown in Fig. 6. (Pl. II.) by ACB) will be

represented by the ordinates of some curve $m n o p q$, cutting the axis at the neutral points $n p$. They reach their maximum at m and q , where they have the same character, and also at o , where they have an opposite character; and they vanish at n, p , the points which correspond to the black spaces.

PROPOSITION XIII.

The upper edge of the plate which polarises the highest tint in the second exterior set of fringes, has received no sensible accession of heat, and the central parts of the plate, which form the two interior sets of fringes, exhibit no variation of temperature connected with the colours which they polarise. When the number and form of the plates of glass, and the temperature of the source of heat remain the same, the magnitude of these three sets of fringes depends upon the law of the decrease of temperature at that part of the glass which produces the first exterior set.

It will be seen from experiments given under a subsequent Proposition, that the depolarising structure is communicated to the upper edge of the plate of glass, even when it is 2, 4, 5, 6, and 7 inches high. In some of these cases, the edge of the glass has the same temperature as the circumambient air, although the heat necessary to produce the same fringe at the lower edge of the plate, is much greater than that of boiling water.

By spreading over the surface of the plate a thin film of oil of mace, which melts with a slight degree of heat, I was enabled to ascertain that there was no particular variation of temperature connected with the tints which were polarised by the three sets of fringes mentioned in the Proposition.

In every case the number of fringes in these sets increased and diminished with the number in the first exterior set. Their breadth also varied with the breadth of the fringes of the first exterior set, and consequently depended on the law of the decrease of temperature in that part of the glass.

SCHOLIUM.

The truth contained in the preceding Proposition, will, I have no doubt, be regarded by philosophers, as one of the most extraordinary in physics. The production of a crystalline structure in the part of the glass adjacent to the heated iron, though a curious property of radiant heat, is in no respect hostile to our established notions. But the communication of the same structure to the remote edge of the glass, where there is no sensible heat, and where the corpuscular forces, by which the particles cohere, are not weakened by any approximation to fluidity, and the existence of an opposite structure in the middle of the glass, developing itself on both sides from a central line, are results to which we can find nothing analogous, but in the perplexing phenomena of magnetical and electrical polarity.

PROPOSITION XIV.

When a plate of glass heated uniformly, and having a temperature considerably above that of the atmosphere, receives a crystalline structure in cooling, as described in Prop. II. the parts which produce the four sets of fringes have each a structure opposite to that which they had when the plate was crystallized by the introduction of heat from without. That is, the parts of the glass which afford the two exterior sets of fringes, have the same structure as the class of doubly refracting crystals, in which the extraordinary ray is repelled from the axis, and the parts which form the two interior sets of fringes, have the same structure as the class in which the extraordinary ray is attracted to the axis.

I took 12 plates of mirror glass, and brought them to an uniform heat by laying them successively on their sides and edges upon a bar of hot iron. Having ascertained, by exposing them to a polarised ray, that they had no action upon light, I placed them with their edges upon a cold iron, so as to exhibit distinctly the white fringes of the four different sets. When the axis of a plate of a sulphate of lime, which polarised a blue of the second order, was placed at right angles to the direction of the fringes, the white of the two exterior sets was converted into a *brownish red*, and the white of the two interior sets into a light *green*. The converse of this happened, when the axis of the sulphate of lime was coincident with the direction of the fringes. When the four white fringes are produced by placing the glass upon a hot iron, all these phenomena are reversed, the *green* tint being now produced

instead of the *brownish red*, and the brownish red instead of the *green*.

The same result was obtained by combining glass plates crystallized in these two different ways.

In order to obtain a still more uniform temperature, I took a parcel of 15 crown glass plates, and suspended them in a vessel of boiling water, at some distance from the bottom. As soon as they had acquired the temperature of the water, I lifted them out, and placed them with their edges on a cold iron. The black spaces and fringes immediately appeared, and a yellow tint was visible in the middle of the interior fringes. The interior fringes had the same properties as the exterior fringes described in Prop. VIII. and *vice versa*. This experiment was frequently repeated with the same result.

The fringes produced in this manner, we shall call the *unusual series* of fringes, in opposition to the *usual series*, or those produced by placing cold glass upon a hot iron.

I was now anxious to observe the phenomena that would be presented by inducing the *unusual series* of fringes upon a parcel of plates that already possessed the *usual series*. In order to effect this, I placed the parcel of 15 plates of glass, already mentioned, with their edges on the bottom of a vessel filled with boiling water.

The bottom of the vessel being very hot, communicated to the parcel of plates the *usual series* of fringes, just like a plate of hot iron. When the parcel was taken out and placed upon a cold iron, the *usual series* of fringes was distinctly seen; but after the lapse of some seconds, it gradually disappeared, and was displaced by the *unusual series* advancing from the edges, and occasioned by the cooling of the plates. The

struggle between the advancing and retiring fringes, had a curious appearance. Before the usual series of fringes vanished, the external fringes became broader, while the middle one gradually diminished. The two black spaces met in the middle of the plate, forming a broad undefined dark space, and the new or unusual series were seen advancing from the edges of the glass. At this instant there were two white spaces in the middle of the plate, and two external ones, but one of the middle white spaces quickly died away, and the unusual series was speedily developed.

If plates of glass that exhibit the usual fringes are taken from the hot iron and allowed to cool in the open air, the fringes will gradually pass away as described in Prop. VI. but, as soon as they disappear, or a little before their disappearance, the opposite sets begin to advance upon the plate in the manner already described.

PROPOSITION XV.

When similar fringes of the usual and unusual series are combined symmetrically, the polarised tint is that which is due to the difference of the thicknesses, but when they are combined transversely, the tint is that which is due to the sum of the thicknesses of the plates. When dissimilar fringes of the two series are combined symmetrically, the polarised tint is that which is due to the sum of the thicknesses, but when they are combined transversely, the polarised tint is that which is due to the difference of the thicknesses of the plates that produce them.

The preceding truth was established by combining the fringes produced by 15 plates of crown glass cooled from the heat of boiling water, with those produced by a plate of glass

placed on a hot iron. The effects produced by the transverse combination will be understood from Fig. 7. (Pl. II.) in which C, C, &c. represent the similar fringes where the combined effect is produced, and DD, &c. the dissimilar portions where the difference of the effect is produced. The portions C, C, &c. will therefore polarise tints higher up the scale than any that are polarised by the plates singly, whereas the portion DD, &c. will polarise tints much lower on the scale than any of those polarised by the single plates.

When the tints of the *usual series* are of the same intensity with those of the *unusual series*, the effect of crossing is very beautiful, and is represented in Fig. 8. (Pl. II.) where the portions corresponding to C, C, &c. are obviously affected with high tints in the scale, while those corresponding to DD, &c. are almost entirely black. The tint polarised in the central fringes of the plates, when separate, was the commencement of *yellow*. The combined tint, in the figure of a round circular spot, was a beautiful *indigo*, which appeared at the centre of the square of intersection ABCD. This gradually shaded off through all the lower tints, and terminated in a dark circular fringe. Beyond this fringe, towards the angles A, B, C, D, an opposite set of fringes were seen; but towards the sides nothing but a dark shade was visible. All these phenomena are the necessary results of the principles already laid down.

SCHOLIUM.

The phenomena described in the Proposition are the same as those which are exhibited by crossing plates of the two classes of doubly refracting crystals. The former, are however, far more beautiful than the latter.

PROPOSITION XVI.

To explain the effects produced upon the fringes by varying the height of the glass plates.

In order to observe the changes occasioned by increasing the height of the plates, I employed pieces of glass whose height varied from 0.18 of an inch to 8 inches. When the height is very small, and not above 2 inches, the black spaces occupy nearly the position as shown in Fig. 2. (Pl. II.) The fringes are therefore very small, as they must always diminish with the height, but they are remarkably brilliant, and exhibit much beauty in their developement.

When the plates exceed two inches in height, the distances NP, PE, Fig. 2. (Pl. II.) increase much faster than ND; a smaller number of fringes is developed beyond OP, and their brightness is much impaired. (This effect is shown in Fig. 9. Pl. II.) When the plates are 8 inches high, the whole fringe is faintly seen above OP. The colours of the two interior fringes are developed from a line much nearer MN than OP, and the black fringe OP is extremely indistinct. As high plates almost always burst in pieces when the maximum tint is nearly produced, I was obliged to use plates of common window glass, but, on account of its dark green colour, I could not examine the phenomena with much satisfaction; in using parcels of these large plates, much caution is necessary, as there is almost a certainty of some of them bursting with violence during every experiment.

PROPOSITION XVII.

To explain the effect produced upon the fringes by varying the shape of the glass plates.

When the breadth of the plates is very small compared with their height, the black spaces have the form shown in Fig. 10, 11. (Pl. II.) the breadth AB of the former being 0.8 of an inch, and that of the latter 2.25 inches. In Fig. 10. (Pl. II.) the upper black space ABCD was indistinct about CD, and was scarcely separated from the lower black space E 3 F. Coloured fringes appear at 1, 2, 3, and a white space between AB, CD extending pretty high, and growing gradually fainter, the parts 1, 2, have the same tint, and the parts 3, 4, the opposite tint. With a piece of glass whose height AC was $4\frac{1}{2}$ inches, its breadth AB 4 inches, and its thickness $\frac{4}{10}$ of an inch, I obtained an effect similar to what is represented in Fig. 11. (Pl. II.) The lowest part of the black fringe above 2 was $1\frac{1}{2}$ inch above CD, and the space at 4, all the way to the edge AB, was a pale bluish white. There were numerous fringes between C and D. In Fig. 11. (Pl. II.) the black spaces AB CD, and EF were separated by a whitish space 2. The portions 1, 2, 3, had the same tint, and the portions 4, 5, the opposite tint. See Prop. XXXVI.

The form of the black spaces and the fringes varies in general with the outline of the plates. When the lower edge CD, Fig. 12. (Pl. II.) had a waving form, and was placed upon a hot iron, the adjacent black space had likewise a waving form, and the parts M, N, though the most distant from the source of heat, polarised tints higher in the scale than the parts O, P.

In a piece of glass shaped as in Fig. 13. (Pl. II.) when CD was heated, part of the upper black space had the form abc , and the other part ef , terminated at f .

PROPOSITION XVIII.

To explain the effects produced upon the fringes by an interruption in the continuity of the glass.

If the second exterior and the two interior sets of fringes were caused by the actual communication of heat to the parts of the glass which produce them, there was reason to believe, that they would not be affected by any breach of continuity in the glass, which did not obstruct the progress of the heat. In order to determine this, I broke a plate of glass ABCD, Fig. 14. (Pl. III.) through the middle mn , and having obtained a very clean fracture, I placed the upper fragment CD, upon the lower one. This compound plate was set upon the hot iron RS; but no effect was produced on the upper plate, the fringes developing themselves in AB, just as if CB had been removed. When the heat was almost uniformly diffused over AB, CD began to exhibit faint traces of the white fringes, AB now serving as a new source of heat. The very same result was obtained when the two plates were joined by the interposition of *water*, *Canada balsam*, or *rosin*.

I now took a piece of glass ABCD, Fig. 15. (Pl. III.) interrupted by a fissure, or crack mn extending a short way into the plate. When the heat was communicated to its lower edge, the fringes were seen above mn , as if the crack had not existed, and the depolarised white light appeared condensed at n , like a fluid rushing round the point. The crack, however, suddenly extended to o ; the upper piece of glass

flew off with violence from the lower one, and a black fringe instantly sprung up below the new edge mo , just as if the upper part of the glass had never been in contact with the lower part. In another experiment, attended with the same result, the crystalline structure above mn instantly vanished when the crack reached o , although the two pieces of glass still cohered with some force. When the fissure mn was placed vertically, as in Fig. 16. (Pl. III.) the same effect took place as if the two pieces had been separate, and no change was observed by cementing them with Canada balsam.

Instead of fissures, I now substituted deep grooves cut across the glass. A thick plate which had a horizontal groove cut half through it, and extending from edge to edge, was laid upon the hot iron. The white fringes appeared imperfectly above the groove, and an undefined dark wave below it, as if some fluid had been obstructed in its passage through a narrow channel. It is not improbable that this dark wave was occasioned by the combination of two white fringes of different sets. For if BC, DE , Fig. 17. (Pl. III.) be a vertical section of the plate, and AFG the groove, the parts $GFomE$ may be considered as acting like a separate plate, and will therefore have op, mn for its black spaces, while the other part, $DBC AFom$, will also act as a separate plate, and have tu, rs , for its black spaces. But the white of the exterior fringe of the first of these plates between FG and op will thus be opposite to the white of one of the interior sets in the other plate, and as these are produced by opposite crystallizations, a black tint will be the result of their union. The bursting of the plate in the direction of the groove, prevented any farther examination of the phenomena.

I next took a plate of glass that had a diamond cut across the middle, where the interior white fringes appeared. Having broken it in two, a black fringe instantly arose between the cut $m n$, Fig. 14. (Pl. III.) and the plate displayed all the interior sets of fringes without receiving an additional supply of heat.

I now attempted to bring the two separated surfaces into close contact by grinding them upon each other; but I could not succeed in making them act upon light like a single plate. The following method, however, enabled me to surmount the difficulty, and to obtain some new results.

I took a piece of annealed crown glass of the size represented in Fig. 52. (Pl. V.) about 0.42 inches thick, and 0.5 broad, and having made a notch with a file at the point B, I applied to it a heated iron, which instantly produced a fissure $B b c d$, and intercepted all the incident light by the total reflection which was produced. After standing an hour, this fissure began to disappear, and in the course of a day, it was as completely closed up as if it had never been made. The fissure was frequently reproduced by a hot iron; and it regularly closed, unless when the expansive effect of the heat was capable of separating the surfaces to too great a distance. Sometimes it closed in a few seconds, and at other times a little mechanical pressure was requisite to effect the reunion. When the fissure was open, I laid the glass upon a hot iron, and it quickly produced the fringes shown in Fig. 53. (Pl. V.) where the phenomena are exactly the same as if the two pieces AB, BD, had been completely separated. But when the fissure was closed, and the glass laid upon the hot iron, it exhibited the different sets of fringes as shown in Fig. 54. (Pl. V.) just as if it had been one continuous mass.

Now it is manifest, that the two pieces AB, BD, though they touch one another optically, are not in physical contact, or in the same state in which they were before the fissure was formed. If we were to make several other notches in the glass with a file, it would always break at the place of the fissure; which proves that the force of cohesion has there been weakened, and that the surfaces, though optically in contact, are physically at a distance. The crystallization of the solid AD, as if it were continuous, forms a fine analogy with the curious fact in magnetism, that two bars of steel pressed together at their extremities, may be magnetised as if they had formed only a single bar, and will exhibit a neutral point at the place of junction.

PROPOSITION XIX.

When heat is propagated from the centre of a plate of glass in radial lines, all the fringes and the black spaces form concentric circles, and four black radial spaces, at right angles to each other, diverge from the centre in directions parallel and perpendicular to the plane of primitive polarisation.

I took a large plate of glass, and applied to its centre a ball of red hot iron. The four black radial lines were distinctly seen diverging from each other at right angles, but the two concentric dark spaces were indistinctly developed. I next intended to grind a hole in the centre of the plate, and to place in it a red hot ball, but having discovered a much better method of generating the circular fringes, which will be explained in the next section, I proceeded no farther in the experimental illustration of the Proposition.

If we suppose ABCDEFGH, Fig. 18, (Pl. III.) to be eight

equal plates of glass placed upon the faces of octagonal bars of hot iron, the black spaces and fringes will have likewise an octagonal form, abstracting the effects which take place at the extremities of the plates. Now if light polarised in a plane inclined 45° to the horizon, is transmitted through this system of plates, the fringes will be distinctly seen in the four plates A, C, E, G, because their depolarising axes are all coincident with the plane of primitive polarisation, but no fringes will be seen in the plates B, D, F, H, as their depolarising axes are inclined 45° to the plane of polarisation. If this system of plates be now turned round the centre O, each of them will exhibit its fringes when it comes into the positions A, C, E, G. These fringes will gradually disappear during the motion of the plates into the positions B, D, F, H, where they will cease to be visible.

Let us now suppose, that the hot iron is applied to the centre of a circular plate of glass A B C D E F G H Fig. 19. (Pl. III.) the black spaces will obviously have a circular form *a b c d e f g h* and A B C D E F G H; and as the neutral axis of each elementary plate, into which we may suppose the circle of glass to be divided, is directed to the axis O, the dark positions will still be B, D, F, H, and consequently there will be a black cross B *b f* F, D *d h* H, having its arms inclined 45° to the horizon. This cross will continue in the same position during the rotation of the plate about its centre O, every elementary plate losing its depolarising power when it comes into the lines B *b f* F, D *d h* H.

PROPOSITION XX.

When heat is propagated from two different sources, in contact with the opposite edges of a plate of glass, the different sets of fringes preserve the same character, the only effect of the additional heat being to polarise higher tints in the different sets of fringes.

I placed 12 plates of window glass upon a hot iron, and when the different sets of fringes were distinctly visible, I held another bar of hot iron in contact with their upper edges, and observed higher tints polarised in all the four sets of fringes. Many of the plates, however, burst with great violence, so that I could not perceive the phenomena that took place when the diffusion of the heat became more uniform.

PROPOSITION XXI.

When heat is propagated through calcareous spar, rock crystal, topaz, beryl, the agate and other minerals that have the property of double refraction, no optical change is produced in their structure.

The greatest heat which I could conveniently apply to doubly refracting crystals, produced no change whatever in their action upon light, whether the heat was propagated in the direction of their neutral, or of their depolarising axes. These crystals appear to be in the state of steel bars saturated with magnetism, which cannot acquire any additional impregnation. Being already in a state of perfect crystallization, they are not capable of receiving from heat any addition to their crystalline structure.

PROPOSITION XXII.

When heat is propagated through muriate of soda, fluor spar, obsidian, semi-opal, and other minerals that have not the property of double refraction, they exhibit the same phenomena as heated glass.

A mass of muriate of soda, when laid upon a hot iron, exhibited a yellow of the first order, both in the external and internal fringes. *Fluor spar* was very slightly affected. *Semi-opal* suffered a greater change; and *Obsidian* displayed the fringes as readily as glass. A piece of *Obsidian* of considerable transparency, and about $\frac{1}{7}$ of an inch thick, possessed naturally the fringes produced by heat. It must therefore have been formed by igneous fusion. This specimen, for which I was indebted to Mr. SIVWRIGHT, was cut out of a round mass, and preserved its original outline. It probably was of the first variety discovered by Sir GEORGE MACKENZIE.*

Rosin, gum copal, horn, amber, tortoise shell, the indurated ligament of the *chama gigantea*,† and various other sub-

* Sir GEORGE MACKENZIE has observed, that there are two very distinct varieties of obsidian. One of these transmits light when cut into thin plates, which, however, seldom appear of an uniform degree of transparency. This variety, at a temperature much under that which can be excited in a common fire place by a pair of bellows, swells, and is converted into pumice by the extrication of a gaseous fluid, which Sir GEORGE MACKENZIE and Dr. JOHN DAVY attempted without success to collect. During the experiment, the smell of nitrous acid was very perceptible. The other variety is denser, of the deepest black colour, and is scarcely translucent at the edges of thin fragments. It does not swell on the application of heat, much more intense than what converts the other variety into pumice. Should this note meet the eye of a skilful analyst, he would do a service to mineralogy by examining both varieties, and by comparing the analysis of pumice with that of the pumice formed from the first variety.

† I have been indebted to Dr. FRANCIS BUCHANAN, F. R. S. for this curious substance. It is as hard and transparent, and has as rich a colour as amber.

stances, both of animal and vegetable origin, receive a new structure during the propagation of heat.

SECT. II. *On the permanent effects produced upon glass by the communication of its heat to surrounding bodies.*

The phenomena described in the preceding Section are of the most transitory nature. Every fringe is in a state of perpetual change: one colour quickly succeeds another, and after heat has rapidly developed all the various tints due to its intensity, they repass through the same hues which they exhibited in their formation, and they finally disappear after a slow and gradual decline. In this respect, only, do the phenomena of crystallized glass differ from those of the regularly organised bodies that compose the three kingdoms of nature. The fine display of colours which characterises the action of crystalline laminae upon polarised light, are in every respect permanent. The same mineral possesses an invariable structure, and patience only is necessary to detect the phenomena which it presents, and to obtain an accurate knowledge of the character and intensity of its action. The coloured fringes of heated glass, on the contrary, are not susceptible of correct mensuration. Where every thing is in a state of change, no fixed character can be seized, and, instead of measuring, it is often difficult to observe their variations. From this perplexity, however, I have been fortunately relieved by the discovery of a method of fixing glass in a crystalline state, and giving it a character as permanent as that of the most perfect minerals. An account of this method, and of the results which it has enabled me to obtain, will form the subject of the present Section.

PROPOSITION XXIII.

When a plate of glass brought to a red heat is cooled in the open air, or is placed with one of its edges upon a bar of cold iron, the different sets of fringes described in Section I. are developed during its cooling, and they have the same character with those which are produced by placing cold glass upon a hot iron. When the cooling is completed, the structure which affords the fringes, becomes permanent, and the colours, when thus fixed, possess the same brilliancy which they displayed during their formation.

When the red hot plate is exposed to a polarised ray, it exhibits at first no action upon light; the tints advance slowly from the edges, and, after the lapse of 12 or 15 minutes, the glass is cooled, and the crystallization complete.

In this way I have formed various plates of glass which possess a permanent structure, and exhibit the phenomena described in the Proposition, but not having obtained a complete series of different heights and thicknesses, I have not yet taken any exact measurements of the fringes.

The following results with four different plates of glass, will convey some idea of the nature of the tints which are developed. All the plates were brought to a red heat so as not to lose their shape, and were cooled by placing their lower edges upon iron of the same temperature as the surrounding air.

	Thickness of the plates.	Maximum tint at the lower edge.	Tint in the middle.	Numbers in Newton's Table corresponding to the maximum tint.
No. 1.	0.1125 inch	{ Beginning of blue of the 2d. order.	Blue of the 1st. order.	8.7
2.	0.2000	{ Green of the 3d order.	Beginning of blue of the 2d. order.	16 2
3.	0.2833	{ Green of the 4th order.	Beginning of purple of the 1st. order.	22.7
4.	0.4375	{ Nearly end of the red of the 5th order.	Pink of the 2d. order.	35.5

By comparing the numbers in the 5th column, which are millionth parts of an inch, with those in the second column, it will be found that the constant factor, by which we must multiply the thickness of any plate of glass, in order to obtain the thickness of the plate which would afford by reflection a tint similar to its maximum tint, is nearly $\frac{1}{12580}$.

It is a curious circumstance, that the permanent fringes have precisely the same character as the transient fringes which are produced by placing glass plates upon a hot iron, while the transient fringes, developed during the cooling of glass plates, have an opposite character.

The limiting temperature at which the former are changed into the latter, is probably that, at which the permanent structure is communicated.

When the glass plates are cooled more at one edge than at another, the fringes are less distinct, and the tints lower at the edge that is least rapidly cooled. This difference becomes more perceptible as the height of the plates is increased.

When the plates of glass are thick, and exposed to a considerable heat, they often lose their polish, and exhibit on their surface a delicate fibrous texture when examined by a microscope. This texture sometimes consists of grooves which exhibit by reflection the coloured images produced by mother of pearl. It also communicates the same property to wax.

PROPOSITION XXIV.

When a plate of glass, crystallized in the manner described in the preceding Proposition, is inclined to the polarised ray in a plane perpendicular to the direction of the fringes, the central tints ascend in the scale of colours, as if the plate had increased in thickness; but, when it is inclined in a plane parallel to the direction of the fringes, the central tint descends in the scale, as if the plate had become thinner. When the plane of inclination forms an angle of 45° with these planes, no change is produced in the tints.

I took a plate of crystallized glass which polarised in the line *a b*, Fig. 2. (Pl. II.) a broad but very faint tinge of yellow; when it was inclined in a plane perpendicular to the direction of the fringes, the tint which it polarised became a dark orange yellow—but, when it was inclined in a plane at right angles to the former, the tint became a pale bluish white. A similar result was obtained, when the colours belonged to higher orders in the scale.

The effect of inclination may be seen more advantageously when two plates that polarise the very same tint, are placed transversely, so as to exhibit the cross represented in Fig. 3. (Pl. II.) By inclining one of the plates, the other is necessarily inclined in an opposite plane, so that the tints of the one *ascend*, while those of the other *descend* in the scale of colours.

The consequence of this is a separation in the middle of the cross, producing two curved black fringes, having the same appearance that is afforded by crossing two plates that polarise different tints.

PROPOSITION XXV.

If a plate of crystallized glass is cut in two pieces by a diamond along the line ab , Fig. 20. (Pl. III.) each of the separate plates will exhibit the properties of a whole crystallized plate. The portion $rsop$ of the separate plate which had formerly the structure of the attractive class of doubly refracting crystals, has now the structure of the repulsive class; another portion op which had the attractive structure, has now an intermediate structure, similar to that of muriate of soda, &c.* and so on with the other parts of the crystal.

If a plate of crystallized glass ABCD, Fig. 20. (Pl. III.) is cut with a diamond along the line ab , through the central white fringe, the portion ab DC has the same structure as the whole plate, as is represented at rs GH, Fig. 21. (Pl. III.) a dark space having started up at op , while the other dark space MN has descended to mn ; the portion $rspo$, mn GH, have now the structure of the repulsive class, and the intermediate portion $opnm$, that of the attractive class of crystals.

The same change takes place in the upper plate ABba, Fig. 20. (Pl. III.) which has the appearance shown at EFsr Fig. 21. (Pl. III.) In one case I found that the fringes in the upper plate were exactly the reverse of those in the under plate.

When the plate is cut perpendicularly to the fringes, an analogous effect is produced. *Terminal* fringes instantly ap-

* See the *Transactions of the Royal Society of Edinburgh*, Vol. VIII. Part I. where the properties of this intermediate class of crystals are described.

pear at the new extremities. A similar, though a more unexpected result, was obtained by breaking in pieces a large plate, in which the crystallization was extremely irregular, polarising here and there a portion of white light. The plate had a small crack in it, and when broken in three pieces, principally along a line nearly parallel to its edge, each piece was regularly crystallized, having the two black spaces with their accompanying fringes of white light.

The same effects are produced when the plate is cut in pieces by a slitting wheel, or has its shape altered by grinding.

The preceding experiments are not easily made, as it is very difficult to cut this kind of glass with a diamond. It generally flies into many pieces as soon as it is scratched, and, when this does not happen, the pieces separate of their own accord, some time after the diamond has been applied.

SCHOLIUM.

The truth contained in the preceding Proposition is analogous to the celebrated experiment in magnetism, where the smallest portion detached from the extremity of a magnet, becomes itself a complete magnet, possessing distinct north and south poles. The exhibition of the same phenomena in glass transiently crystallized during the propagation of heat, as described in Prop. XIII., might have been supposed to arise from some new property of heat, which enabled it to act on the remote edge of the glass without any sensible indication of its presence. This opinion, however, is to a certain extent excluded by the results obtained with glass permanently crystallized and having an uniform temperature. Any portion of the glass passes with the utmost facility from one crystalline

structure to the opposite structure, and from one degree of crystallization to another, according to its position with regard to the edge of the plate; and there cannot be an equilibrium among the forces, by which this change is produced, unless the plate exhibits the different sets of fringes which have already been described.

This optical polarity is produced by heat, just as electrical polarity is developed in the tourmaline, and other minerals by the same agent; and there is as much reason to ascribe the production of the optical phenomena to the action of a peculiar fluid, as there is to explain the phenomena of electricity and magnetism by the operation of magnetical and electrical fluids. The optical fluid, as we may call it, may be supposed to reside in all bodies whatever in its natural state, consisting of two fluids in a state of combination, and capable of being decomposed, and fixed in particular parts of a body by the agency of various causes. It would be a waste of time to point out the numerous and striking analogies, which exist between many of the results contained in this Proposition and some of the most interesting phenomena of electricity and magnetism. Some of them will be noticed in the demonstration of a subsequent Proposition.

PROPOSITION XXVI.

When a rectangular plate of glass is brought to a red heat, and cooled as already described, it will acquire such a permanent structure as to exhibit the coloured fringes when polarised light is transmitted through any of the parallel faces by which it is bounded; every rectangular plate being considered as a solid contained by six parallel planes. The depolarising axes are distinctly developed in all these directions, and form angles of 45° with the common sections of the planes.

The fringes described in the Proposition are extremely minute, in plates of glass of an ordinary thickness. They consist of the same number of sets, having the same character and properties as those seen through the broad surfaces of the plates, and their maximum tint is generally lower, though sometimes higher, than the maximum tint of the large fringes produced by the broad surfaces. They are in general perfectly regular, even when there is a great degree of irregularity in the form of the large fringes. In a plate of glass which had various breadths, and which polarised a faint yellow of the first order in its central fringes, and a bright blue of the second order in its exterior fringes, the central tints seen through its edges varied with the breadth of the plate, from a faint yellow of the first order, to a deep blue of the second order.

In order to examine with more accuracy the fringes formed by transmitting polarised light through the different faces of a plate of glass, I crystallized a rough parallelepiped of crown glass, which was about three inches long, and half an inch

thick, and when it was properly cut, and polished on a lapidary's wheel, it had the dimensions shown in Figs. 22, 23, and 24, (Pl. III.) The fringes seen through its two broadest surfaces are represented in Fig. 22. (Pl. III.) The maximum tint of the central fringes is the commencement of the *green* of the second order, and that of the exterior fringes a *green* of the third order. In the fringes seen through the edges of the plate, which are shown in Fig. 23. (Pl. III.) the maximum tint of the interior set is a yellow of the second order, and that of the exterior set is a green of the third order. The fringes seen through the ends of the glass plate are very curious, and are represented in Fig. 24. (Pl. III.) where A shows their form when the line AB is inclined 45° to the plane of primitive polarisation, and B their form when the line AB is parallel, or perpendicular to that plane. I have another parallelepiped of flint glass, about 4.3 inches, by 1 broad, and 1 inch deep, which was crystallized when in the form of a cylinder, and afterwards ground into the shape of a parallelepiped. It exhibited the same phenomena as the preceding, and equalled it in the fine display of numerous orders of colours. The beautiful figures produced by crossing these two pieces, surpass in splendour every optical phenomenon that I have seen.

In these and several other specimens of very thick crystallized glass, the maximum tint was always diminished by the operations of grinding and polishing.

The following descriptions of four specimens of crystallized glass will point out the effects which are produced by changing the form of the plate.

No. 1. One of the most curious specimens of crystallized glass which I have obtained, is a parallelopiped about 0.38 of an inch broad and deep, and 1.11 inch long. It depolarises a faint yellow of the first order in the central fringe, when polarised light is transmitted through the faces of the parallelopiped. But when the light is transmitted along the axis of the parallelopiped, and when the lines AC, AB are parallel or perpendicular to the plane of primitive polarisation, the two images formed by calcareous spar exhibit the forms represented in Figs. 25, 26. (Pl. III.) The first of these consists of a black cross surrounded with beautiful fringes of contrary flexure, and has bright green spots of the third order with a little yellow of the same order; their centre at the four angles, A, B, C, D. Figure 25. (Pl. III.) exhibits a form exactly complementary to Fig. 26. (Pl. III.) and remarkable like it for the symmetry of its form. The coloured spots at the angles are now a brilliant pink, with a spot of blue in the middle of them. When the lines AB, AC are inclined 45° to the plane of primitive polarisation, the two images exhibit the forms represented in Figs. 27, and 28, (Pl. IV.)

No. 2. Is another piece of glass of a square form, and 0.3 of an inch thick, it produced the central cross, and exhibited at the angles all the tints up to the blue of the second order arranged in circles, having the blue or maximum tint in the centre. See Figs. 29 and 30. (Pl. IV.)

No. 3. A third plate 0.4 of an inch thick produced the same effect, the angular tints rising in this case to the yellow of the second order.

No. 4. A fourth plate, 1.2 inch thick, produced fringes of contrary flexure like those of No. 1, but rising to the pink of the fourth order.

The terminal and lateral fringes are produced by No. 2, 3, 4, when they are turned round 45° . Their complementary fringes are extremely beautiful.

When No. 2 is combined with No. 3, they produce fringes of contrary flexure like No. 1. The nature and origin of all these fringes are explained in a subsequent Proposition.

PROPOSITION XXVII.

If a rectangular plate of crystallized glass which exhibits the fringes through its edges is inclined to the polarised ray in a plane perpendicular to the direction of the fringes, the central tint will descend in the scale as if the plate had increased in depth; but when it is inclined in a plane parallel to the direction of the fringes, the tint will ascend in the scale as if the plate had diminished in depth.

The result contained in this Proposition was established by the same experiments which are described in Prop. XXIV., the fringes seen through the edges of the plate being used instead of those seen through its broad surfaces. The effects of inclination in these two cases are directly opposite.

PROPOSITION XXVIII.

The regularity in the crystallization of a plate of glass according to one of its dimensions, is not disturbed by any irregularity of its crystallization in another direction.

If a plate of glass is crystallized from a centre, as in Prop. XIX., or if a confused crystallization is induced by cooling it at different places, so that no distinct fringes can be seen when polarised light is transmitted through the broad surfaces of the plate, the fringes seen through its edges will be perfectly

developed, and will possess the same properties as if the whole plate had been regularly crystallized.

PROPOSITION XXIX.

At the extremities A, B of every plate of crystallized glass, there are four portions N, S, N' S', at the boundary between the terminal and the lateral fringes, which possess a structure different from the rest of the plate. These portions have their axes inclined to axes of the other parts of the glass. The portions N, N have their axes in the same direction, and S, S' in a direction opposite to those of N, N'.

When a plate of crystallized glass is exposed to a polarised ray, so that its length in the direction of the lateral and central fringes is parallel or perpendicular to the plane of primitive polarisation, it will exhibit the appearance shown in Fig. 31. (Pl. IV.) where all the lateral, central, and terminal fringes have vanished. Four luminous spots, however, N, S, N', S', will be seen at the extremities A, B, exhibiting tints which, in general, vary from the white of the first order to the pink of the second order, and sometimes exceed, and sometimes fall below, the maximum tint of the central fringes. In order to examine the nature of these tints, I took a plate of glass, which when held in the position already mentioned, polarised at the points N, S, N', S', a blue of the second order. I then combined with it a plate of sulphate of lime which polarised the same tint, and which had its axis inclined 45° to the plane of primitive polarisation. The resulting tints at the angles N, N', were black, or that which was due to the difference of their actions, while the resulting tint at S, S',

was green, or that which was due to the sum of their actions. The same result was obtained when I combined with the above plate the *central* part of another crystallized plate which had the direction of its fringes inclined 45° to the plane of primitive polarisation.

When the axis of the plate of sulphate of lime was turned round 90° , or when the blue tint was taken from the lateral fringes of a plate of crystallized glass, having the direction of its fringes inclined 45° to the plane of primitive polarisation, an opposite effect was produced, that is, the resulting tint of the portions S, S', was black, and that of the portions N, N', green.

In two crystallized plates of a square form which afforded the lateral sets of fringes C, D, and the terminal sets A, B, but no central sets, as shown in Fig. 32. (Pl. IV.) the portions N, N', S, S', had the structure described in the Proposition. When the plate was held with the line A, B, parallel or perpendicular to the plane of primitive polarisation, it exhibited the phenomenon shown in Fig. 33. (Pl. IV.)

When any plate of crystallized glass, as AB, Fig. 31. (Pl. IV.) is cut through at CD, either by a diamond or upon a lapidary's slitting wheel; new fringes, n, n', s, s' similar to N, N' S, S' start up at the new extremities of the plate.

The fringes described in this Proposition may be called the *diagonal fringes*.

PROPOSITION XXX.

In all the phenomena which have hitherto been described, the results are precisely the same, whether the anterior or the posterior face of the glass plate is exposed to the polarised ray; but, in the portions N, N' S, S' the tints change their character, according as one or other of the faces first receives the polarised light.

If the plate *ab*, Fig. 34. (Pl. IV.) has its lower surface exposed to the polarised light, the portions *n, n'* exhibit, when combined with sulphate of lime, a tint due to the difference of their action; and *s, s'* a tint due to the sum of their action; but when the upper surface is exposed, as in Fig. 35. (Pl. IV.) the portions *s, s'* exhibit, in combination with sulphate of lime, a tint due to the difference of their action, and the portions *n, n'*, a tint due to their sum. This curious phenomenon arises from the axes of the elementary crystals suffering an angular change of position, amounting to 90° , by turning the other side of the plate to the polarised ray, as shall be more particularly explained in a subsequent Proposition.

PROPOSITION XXXI.

If a crystallized plate a b, Fig. 34. (Pl. IV.) is placed symmetrically above A B, Fig. 31. (Pl. IV.) either with the two anterior or the two posterior faces coincident, or with the anterior face of the one coincident with the posterior face of the other, or with the end a above A or b above B, or with b above A or a above B, in all these positions the tints polarised by the portions N, N' S, S' will ascend in the scale of colours, and be that which is due to the sum of the thicknesses of the plates. If the extremity a or b is placed above B or above A, so that the lines AB, a, b, form a continuous straight line, the tint polarised by the combination, will descend in the scale, and be that which is due to the difference of the thicknesses of the plates.

The truth contained in this Proposition, has been established by direct experiment, although it might have been deduced from the Propositions which precede it.

PROPOSITION XXXII.

When the neutral axes of a plate of crystallized glass are parallel or perpendicular to the plane of primitive polarisation, both the exterior and interior sets of fringes vanish, if the polarised ray is incident perpendicularly upon the plate; but, if the plate is inclined to the incident ray, four sets of fringes are developed. They are separated from each other by three black spaces, and the fringes on each side of the central black line have the same character.

When the lateral and the central fringes have vanished, the four diagonal fringes A, B, C, D, Fig. 36. (Pl. IV.) alone

appear at a vertical incidence, but, upon inclining the plate to the incident ray, in the direction of its length OP , three black spaces mn , OP , qr , are gradually developed. One of them OP passes through the centre of the plate; and between the black spaces are four sets of fringes 1,1; 1,1; 2,2; 2,2; By examining these fringes with a standard plate of sulphate of lime, and with plates of crystallized glass, I found that the fringes 1, 1, 1, 1, had the same character as the diagonal fringes A, D , while the fringes 2,2, 2,2, had the same character as the other two diagonal fringes C, B . In one plate, where the maximum tint of the interior fringe was a faint yellow of the first order, the fringes 1, 1, 2, 2, consisted of a *blue* of the first order, and in another plate where the maximum tint of the interior fringe was a faint yellow of the second order, the fringes between $m n$ and $q r$ consisted of a *green* of the second order.

PROPOSITION XXXIII.

When a plate of crystallized glass is placed on a red hot iron, the number of its fringes is increased. These additional fringes are the same that would have been produced by combining with the crystallized plate an uncrystallized plate of the same form and thickness, and subjected to the same temperature as the crystallized plate. They disappear when the glass cools, but the permanent fringes are not altered unless the heat be very intense, in which case, they suffer a small diminution.

The results described in the Proposition were obtained by placing crystallized plates upon bars of iron of different temperatures. The plate was held out of the heat of the red hot iron, when its effect was combined with that of an uncrystal-

lized plate. The state of the crystallized plate is analogous to that of a bar of steel not saturated with magnetism. It is capable of receiving from heat a much higher degree of crystallization. See Prop. XXI.

PROPOSITION XXXIV.

When a plate of permanently crystallized glass is brought to an uniform temperature in boiling water, or boiling oil, and is then cooled in the open air, the tints descend in the scale, in proportion to the temperature employed, but, they again resume their former intensity when the plate acquires the temperature of the surrounding air.

This diminution of the tints, arises from the production of the transient and *unusual* series of fringes described in Prop. XIV., which, being of an opposite character from the permanent fringes, necessarily causes them to descend in the scale. The effect is here precisely the same, as if the permanently crystallized plate had been combined, when cold, with a hot plate of the same thickness, oppositely and transiently crystallized by cooling.

PROPOSITION XXXV.

When the centre of a plate of glass brought to a red heat is laid upon the summit of a small cylinder of iron standing vertically, it acquires in cooling a permanent structure which exhibits black spaces, and fringes of a circular form, and the black cross exhibited in Fig. 19. (Pl. III.)

In a specimen of plate glass crystallized in this manner, the dark spaces and the black cross are very distinctly developed, a yellow tint of the first order appearing between the dark

spaces. When polarised light is reflected from this plate at the polarising angle, the preceding phenomena are very finely displayed. The minute fringes mentioned in Prop. XXVI. are also seen by looking through the edges of the plate, and are not affected by the circular crystallization.

PROPOSITION XXXVI.

When a cylinder of glass is brought to a red heat, and cooled in the open air, it acquires a permanent crystallization, in which the principal sections of all the elementary crystals are directed to the axis of the cylinder.

The phenomena exhibited by transmitting polarised light along a cylinder of this kind, about $2\frac{1}{4}$ inches long, and $\frac{6}{10}$ of an inch in diameter, are shown in Figs. 37 and 38. (Pl. IV.) where A B C D, Fig. 37. (Pl. IV.) is the principal image, and *abcd*, Fig. 38. (Pl. IV.) the complementary image. The dark cross AC, BD, instead of having its arms inclined 45° to the horizon, as in Fig. 19. (Pl. III.), has them parallel and perpendicular to the horizon, as the light transmitted through the cylinder happened to be polarised in the plane of the horizon. The luminous spaces between the arms of the cross contain about 10 beautiful rings of coloured light. The complementary image *abcd* is marked with four dark spots, corresponding to the four luminous portions round the central part of the cross, and the outer part has four dark sectors A, B, C, D, corresponding with the light ones in the other image, and formed of small concentric arches of a dark hue, fringed with tints of different colours. In order to see this phenomenon in all its beauty, it is necessary that the polarised ray be exactly parallel to the axis of the cylinder, as the slightest deviation completely destroys the regularity of the figure.

The crystalline structure which exhibits the dark rectangular cross may be imitated, by forming a circle with various sectors of calcareous spar, having the principal sections of each directed to a common axis.

Having had occasion to grind a part of a glass tube into the shape shown in Fig. 39. (Pl. IV.) I was surprised to observe, upon transmitting polarised light along its axis, and analysing it with calcareous spar, that it was depolarised in eight places, 1, 2, 3, 4, 5, 6, 7, 8, Fig. 40. (Pl. IV.) When the line AB was parallel or perpendicular to the plane of primitive polarisation, the tints were of the first order of NEWTON'S scale. The other image formed by the spar, had the appearance shown in Fig. 41. (Pl. IV.) where the dark spots correspond to the white ones in Fig. 40. (Pl. IV.)

In order to discover the origin of these depolarising apertures, I cut another piece out of the same tube and polished the ends of the small cylinder, without grinding off any of the cylindrical circumference. When it was exposed to polarised light, it exhibited the appearance shown in Fig. 42. (Pl. IV.) where ACBD is a dark cross, separating four luminous sectors, and MNOP a dark circular space increasing in darkness towards the points M, N, O, P. If we now suppose the portions *C a b*, *D c d* to be cut off, something like eight luminous apertures will be left, as in Fig. 40. (Pl. IV.) This however is not the cause of the phenomenon. The four apertures on each side of the centre C, are the four diagonal fringes of the square pieces AC, BC, which act as if they were separated at C, the communication being nearly cut off. In this case, the cylindrical crystallization was converted into a rectangular crystallization by changing the shape of the glass. See Prop. XXV.

When polarised light was transmitted through the flat sides of the glass ABCD, Fig. 39. (Pl. IV.) four white spots were depolarised as shown at 1, 2, 3, 4. All these spots have the same bluish white tint, but those marked 1, 2, have their axis at right angles to that of the spots 3, 4.*

The preceding phenomena as explained by the reasoning in Proposition XIX. furnish us with a complete explanation of the appearances exhibited by *oil of mace*, and described in a former paper.† The dark and luminous sectors are obviously produced by circular groups of crystals, having their axes directed to the same centre, and the halo, or nebulous image must be caused by the crystals having a form approaching to that of a sphere. This species of circular grouping is actually seen in a particular kind of *adipocire*, which I have noticed in the Paper already quoted. The axes of the crystals of *adipocire*, however, are not directed to the same centre, and therefore do not exhibit the same phenomena as *oil of mace*.

SCHOLIUM.

The results contained in the Proposition, afford the most satisfactory explanation of the optical properties of PRINCE RUPERT'S drops described in a former Paper. (See *Phil. Trans.* 1815, p. 1.) The cleavages which they exhibit in lines converging to the axis of the drop, and in lines concentric with the outer surface, are necessary consequences of the radial crystallization explained in the Proposition, and may be regarded as an ocular demonstration of its truth.

* These spots are the *diagonal fringes* described in Prop. XXIX.

† See *Phil. Trans.* 1815, p. 38, and 49.

PROPOSITION XXXVII.

When a piece of glass is regularly crystallized, every set of lateral fringes which it exhibits is accompanied with another set of an opposite kind, and the forces by which these fringes are produced, are not in equilibrio, unless when two sets of fringes of one character are opposed to two sets of fringes of the opposite character.

The truth of this Proposition is demonstrated by all the preceding experiments. Some apparent exceptions to it will be stated in the Scholium.

SCHOLIUM.

The result announced in the Proposition, naturally leads us to point out the striking analogy which subsists between the phenomena of crystallized glass and those of magnetism. In order to avoid circuitous expressions, I shall consider the part of the glass which polarises the highest tint in one set of fringes as a *north pole*, and the part which polarises the highest tint in the opposite set as a *south pole*.

1. When heat is propagated along a plate of glass, or when glass is permanently crystallized by cooling, and exhibits the fringes shown in Fig. 2. (Pl. II.), its poles will be arranged as in Fig. 43. (Pl. IV.) which represents a section of the glass across the fringes. The north poles are situated at N, N', and there is a south pole in the middle at S', A, and B being the neutral points corresponding to the black spaces, where the one kind of polarity passes into the other. This arrangement of the poles is precisely the same as that of a

magnetical needle, which has received its polarity by placing the north pole of a magnet upon its centre, and drawing it several times towards the one extremity without returning back again, and afterwards as many times towards the other extremity. The indefinite nature of the poles and fringes, when the plate of glass is high, as described in Prop. XVI. and XVII., and when the heat advances from one edge of the plate, is perfectly analogous to the indefinite polarity communicated to a steel bar, by applying the pole of a magnet to one of its extremities. The same diffused polarity is acquired by hot glass, when one of its edges is cooled much more rapidly than the other. As two distinct poles, therefore, cannot be given to steel, by applying the magnet at one extremity, in like manner a distinct polarity cannot be communicated to glass, either by heating or cooling it solely at one edge, unless when the height of the plate is very small.

Such is the resemblance, indeed, between the two classes of phenomena, that a description of the state and progress of the poles in magnetising a steel bar, is an accurate description of the state and progress of the poles in crystallizing a plate of glass.

2. When a heated plate of glass is cooled in the open air, and produces the transient fringes described in Prop. XIV., the poles are arranged as in Fig. 44. (Pl. IV.) where S, S' are south poles, and N a north pole in the middle, A and B being the two neutral points. This arrangement of the poles is exactly the reverse of the preceding, and is the same as that which takes place in a needle magnetised in the manner already described, but with the north instead of the south pole.

3. In a plate of glass of the same form and size as Fig. 45.

(Pl. V.) the two preceding structures are combined. It has three black spaces, mn , $\mu\nu$, op , the parts D and B have the same structure as that which produces the exterior sets of fringes, and the parts A,C, the same structure as that which produces the interior set in regularly crystallized plates. The poles are therefore arranged in the manner shown in Fig. 46. (Pl. V.) which resembles a magnet with consecutive poles.

4. Out of nearly one hundred pieces of crystallized glass I have found but one which exhibited only two sets of fringes. The piece of glass AB, Fig. 47. (Pl. V.) was intersected in cooling with a crack mEn , which extended completely across the plate. The parts still cohered with such firmness, as not to separate when taken up in the hand. Upon exposing it to a polarised ray, it gave two white fringes E,F, separated by a dark space OP. The two fringes had opposite characters, so that the poles were arranged as in Fig. 48. (Pl. V.) which resembles that of a perfect magnet. This state of the poles, however, is in the case of glass a state of violence, for when the plate broke in two pieces at the crack mEn , the fringes vanished entirely, and it retained no mark whatever of its former crystalline state. The other portion T did not act upon polarised light either before or after the separation. The pressure of the portion T, therefore, had not allowed the other piece of glass to recover from the state of constraint in which it was held.

PROPOSITION XXXVIII.

To explain the origin and form of the different sets of fringes described in the preceding Propositions.

1. *On the fringes produced by rectangular plates.*

It is not easy to ascertain in what manner the various sets of opposite fringes are produced during the heating and cooling of glass, (See Prop. XXXIX.) but it is obvious from the preceding experiments, that when a plate of glass is either transiently or permanently crystallized, all the elementary crystals of which it is composed, turn one of their neutral axes in the direction of the current of heat. The principal axes of the crystals which form the exterior fringes, are parallel to the one edge, and perpendicular to the other. Thus in Fig. 49, (Pl. V.) the axes of the exterior fringes are perpendicular to AD and BC, and the axes of the terminal fringes are perpendicular to AB and DC, while the axes of the interior fringes are parallel to AD and BC.

Let us now consider, what change should take place in the position of the crystals situated at the angles A, B, C, D. An elementary crystal at E will have its neutral axes perpendicular to AD, as it is out of the reach of the forces which act upon the crystals at the edges AB, DC; but, a crystal G in the diagonal AH, BH being similarly situated with respect to the edges AB, AD, will have a tendency to turn its axis both in the direction AB, and in the direction AD, and being unable to obey both these solicitations, it will turn it in the direction of the diagonal AH, forming angles of 45° , with the axes of all the other crystals of which the glass is composed. Any

other crystal a situated out of the diagonal AH, will be acted upon by forces proportional to its distances am , an , from the edges AB, AD, and in the direction of these lines. It will therefore turn its axes in the direction a A the diagonal of the parallelogram $Anam$. In like manner it may be shown, that all the other crystals will turn their axes towards A in lines diverging from A as a centre. Each angular portion, therefore, exactly resembles an inverted quadrant of the cylindrical piece of glass represented in Fig. 37, (Pl. IV.) and described in Prop. XXXIV., and consequently an arm of the black cross will appear in the diagonal AH in every quarter of a revolution. The diagonal portions AH will be dark when all the other fringes are visible, and the diagonal fringes will appear in their full beauty, when the rest have vanished. Since the diagonal fringes at A and C have their axes AH, CH parallel, they will exhibit tints of the same character, and opposite to those of B and D which have their axes BH, DH at right angles to the former. The reason is therefore manifest, why each diagonal fringe changes its character by inverting the plate, for when this inversion takes place the axis of the diagonal portion is put into a position at right angles to its first position.

These observations enable us to explain the appearances shown in Fig. 10, and 11, (Pl. II.) and described in Prop. XVII. In Fig. 10, where the plate is narrow, the black spaces at C and D, bisecting the angles, interfere and nearly obliterate the interior fringes, but in Fig. 11, where the plate is considerably broader, the influence of the angular crystallization does not extend so far, and therefore the interior fringes are seen at 2, Fig. 11. The state of the crystallization at the angles

A, B, C, D, Fig. 49, (Pl. V.) is also peculiar. The glass cools more rapidly there than at any other part, and therefore a higher tint is developed at the angles, than towards the middle of the plate.

2. *On the fringes produced by square pieces of glass.*

If the breadth of the glass plate is equal to its length, as in Fig. 32, (Pl. IV.) all the four diagonal portions nearly meet, and therefore, when the lateral and terminal fringes are developed, the central part is altogether black, as the central fringes have entirely disappeared. When the line AB is parallel or perpendicular to the plane of primitive polarisation, the diagonal fringes appear as in Fig. 33, (Pl. IV.) being always separated from each other by a black space in the form of a cross. This black cross is a necessary accompaniment of the diagonal fringes, for it follows, from the reasoning in Sect. I. of this proposition, that all the crystals situated in the central lines, AB, CD, have their neutral axes in the directions AB, CD, and therefore cease to depolarise the incident light when the diagonal fringes are in full perfection.

3. *On the fringes produced by cylindrical pieces of glass.*

As the heat radiates most copiously from the heated cylinder, in lines perpendicular to its surface, that is, in lines directed to its axis, it follows that the axis of all the elementary crystals will be directed to the axis of the cylinder. The uniformity of the radiation in every part of the cylinder, will produce an uniformity of structure, which will develop similar tints at similar distances from the axis, and thus produce fringes concentric with the cylindrical circumference. The effect of a radial crystallization combined with an angular

crystallization is shown in Fig. 50, (Pl. V.) where ABCD is a plate of glass cooled upon a cylinder of iron at its centre. See Fig. 19, (Pl. III.) and 29, (Pl. IV.)

When the section of the glass is a polygon of any number of sides, the form of its fringes may be easily deduced from the principles which have already been established. When the section is a triangle, no regular figure is seen. If the triangle is equilateral, the lines which bisect the angle, and those which are perpendicular to the sides, are inclined to each other 120° . So that the axes of the crystals are not symmetrically related to the rectangular axes of the particles of light. When the glass is a sphere, the axes are all directed to its centre.

PROPOSITION XXXIX.

To ascertain the probable mechanical condition of the parts of the glass that produce the different sets of fringes.

I have not felt myself authorised to deduce, from any of the preceding results, the mechanical condition of the parts of the glass which produce the different sets of colours. It is obvious that in the case of a red hot plate of glass, cooled in the open air, there is a variable density diminishing from all the edges inwards, but in the propagation of heat along a cold plate, there is no direct argument to prove, that such an increasing density exists at any of the edges, excepting the one adjacent to the source of heat. A similarity, however, in the mechanical conditions of the two plates, may be safely inferred from the perfect similarity of their optical properties. The central part of the crystallized plates, which produce fringes of an opposite character, are in a state of dilatation decreasing

from the central line to each of the black fringes.* This inference is not founded on any direct experiment, but it derives a support almost amounting to demonstration, from a series of new experiments, which I shall soon have the honour of submitting to the Royal Society. These experiments were made by altering the mechanical state of parallelopipeds of animal jellies, both by gradual induration, and by the application of variable pressures; and I have in this way obtained results analogous to those which are described in the preceding paper. In every case the compression of the jelly produced a set of fringes of an opposite structure to those which are occasioned by expansion, and every compression was accompanied with a corresponding dilatation. In like manner it will be found, that there is in all crystallized bodies a variation of density related to their axes, and connected with their polarity, which affords an easy explanation of the fringes of different forms which are exhibited by the various crystals of the mineral kingdom.†

* The appearance of the fracture of glass across the fringes, whether it is transiently or permanently crystallized, is very instructive. It has always the same aspect, and plainly indicates the different mechanical states of the different parts of the glass. From this cause crystallized glass is incapable of being cut with a hot iron, like glass of uniform density, and there is only one way in which the division of the plate can be effected.

† Since this Paper was written, I have discovered that glass, and all other substances that have not the property of double refraction, are capable of receiving it from mechanical pressure, and that a compressing force always produces the structure which gives the exterior fringes in crystallized glass, while a dilating force produces the structure which develops the interior fringes. We are, therefore, entitled to conclude that the middle parts are in a state of dilatation, and the external parts in a state of compression. By a peculiar application of the compressing forces, I have even succeeded in obtaining uniform tints like those produced by plates of sulphate of lime of equal thickness.

PROPOSITION XL.

Radiant heat is not susceptible of refraction, and is incapable of permeating glass like the luminous rays.

The propagation of radiant heat along glass can be rendered visible to the eye by the methods described in the first section of this paper. It advances from the heated edge of the plate, crystallizing the glass during its passage, and producing changes in those parts of the plate where it does not exist in a sensible state.

If the radiant heat is received upon a convex lens, the very same effect is produced. Instead of being bent, like light, at the convex surfaces, it advances, whatever be the angle of incidence, in lines perpendicular to that surface, crystallizing the glass in its progress; and, as soon as it has reached the second surface, it is again discharged, as if from a new source of heat. This experiment I conceive to be an ocular demonstration of the first part of the Proposition.

Dr. Herschel, in his celebrated inquiry into the properties of invisible heat, has deduced the very opposite result from several experiments; but, independently of the minuteness of the effects which he observed, it is manifest, that the thermometer placed in the focus of his lens, received its heat by radiation from the lens itself; and it is also demonstrable, that a convex lens, radiating heat at an uniform temperature, will produce a greater effect upon a thermometer placed in its axis, than upon another having a different position. From the form of the lens, the edges are always the coldest, giving out their heat to the metallic ring in which they are placed,

and therefore, the discharge of heat must be most copious in the direction of the axis.*

The inability of radiant heat to pass through glass, may be considered as a consequence of its refusing to yield to the refractive force; for we can scarcely conceive a particle of radiant matter freely permeating a solid body, without suffering some change in its velocity and direction. The ingenious experiments of M. PREVOST of Geneva, and the more recent ones of M. DELAROCHE, have been considered as establishing the permeability of glass to radiant heat. M. PREVOST employed moveable screens of glass, and renewed them continually, in order that the result which he obtained might not be ascribed to the heating of the screen; but such is the rapidity with which heat is propagated through a thin plate of glass, that it is extremely difficult, if not impossible, to observe the state of the thermometer, before it has been affected by the secondary radiation from the screen. The method employed by M. DELAROCHE of observing the difference of effect, when a blackened glass screen, and a transparent one, were made successively to intercept the radiant heat, is liable to an obvious error.

* The circumstance of the glass cooling most rapidly at the edges, which may be proved by exposing it to a polarised ray, enables us to account for the anomalous and hitherto unexplained fact observed by the younger EULER, that the focal length of a lens is shortened when its temperature is increased. The observation having always been made when the lens was actually cooling, the density, and consequently the refractive power had increased towards the circumference of the lens, and therefore its focal length was diminished.

Might not the spherical aberration of lenses be diminished, and even corrected, by giving them a variable density from their vertex? I have three object glasses of this kind, two crystallized and one uncrystallized, and ground carefully upon the same tool; but I have not yet been able to examine their optical properties.

The radiant heat would find a quicker passage through the transparent screen, and therefore, the difference of effect was not due to the transmitted heat, but to the heat radiating from the anterior surface. The truth contained in M. DELAROCHE's *fifth* Proposition is almost a demonstration of the fallacy of all those that precede it. He found that "a thick plate of glass, though as much, or more permeable to light than a thin glass of worse quality, allowed a much smaller quantity of radiant heat to pass." If he had employed very thick plates of the purest flint glass, or thick masses of fluid that have the power of transmitting light copiously, he would have found that not a single particle of heat was capable of passing directly through transparent media.

PROPOSITION XLI.

To construct a chromatic thermometer for measuring differences of temperature below that of fluid glass, by the optical effects which they produce.

Differences of temperature have hitherto been measured by the expansions and contractions which they produce in solid, fluid, or gaseous bodies, and all the various thermometrical instruments that have been constructed, differ from each other only in the method by which these mechanical effects are rendered visible. The experiments contained in the first Section of this Paper, present us with an entirely new principle for the construction of a thermometer. We have there seen, that the tints polarised by a plate of glass, increase with the temperature by which they are produced, and therefore these tints may be used as a measure of the temperature, after

the tints, corresponding to several points in the thermometrical scale, have been accurately ascertained.

An instrument of this kind which I have constructed, is represented in Fig. 51, (Pl. V.) where ABC is a series of 20 plates of glass, whose length AB is 3.2 inches, their breadth 1.2 inches, and their united thicknesses BC 5.4 inches. A metallic vessel, DEFG, has its bottom formed of a thin layer of tin or lead, or any other suitable metal which can be poured in a fluid state upon the upper edges of the glass plates, so as to touch them in every part. This perfect contact may be obtained for higher temperatures, by grinding the bottom of the metallic vessel till it touches the edges of the glass in every point.

When a heated fluid is poured into the vessel DEFG, its heat will be instantly communicated to the edges of the plates, and when exposed to a polarised ray, subsequently analysed by reflection from a transparent body, they will exhibit the coloured fringes at AB. Now every tint in the scale of colours has a corresponding numerical value, which becomes a correct measure of the temperature of the fluid.

Instead of pouring the fluid into the vessel, we may remove the vessel altogether, and plunge the glass plates into the fluid. They must then be taken quickly out and suspended in a position where they are properly exposed to polarised light. The maximum tint which they develop at the centre, while cooling, is a measure of the temperature which they have acquired in the fluid.

In order to obtain some idea of the nature of the scale, I made the following trials.—The heat of my hand when applied to the edges of 20 plates of glass, produced instantly the fringes with the black spaces. With 12 plates I have

produced the yellow of the first order; and when one plate only was used, the black spaces, and the bluish white fringes were distinctly visible. A temperature of about 80° , that of the glass being 60° , when applied to 20 plates, polarised in the central fringe a *yellow* of the first order, which corresponds to a tint whose value is 4 in the scale of colours. Hence, one plate would have produced a tint corresponding to $\frac{4}{20} = 0.20$ of the scale.

When one of the plates was placed upon a bar of red hot iron, just visible in daylight, it polarised in the central fringe the commencement of the green of the second order, which corresponds to 9.35 in the scale.

Now the difference of temperature answering to 0.20 was $80^\circ - 60^\circ = 20^\circ$. Hence we have

$$\text{As } 0.20 : 9.35 = 20^\circ : 935^\circ$$

the difference of temperature of the iron and the glass. The temperature of the iron is therefore $935^\circ + 60^\circ = 995^\circ$.

If we suppose the tints to be so indefinitely marked that the eye can only observe units of the scale of colours, we shall, even in this case, have a scale of 187 to measure the temperature of $935^\circ - 20^\circ = 915^\circ$, which is a scale having each of its divisions equal to nearly $4^\circ. 9$. The tints, however, are much more definite than we have supposed, for in the second order of colours, in which the observations may always be made, the eight different tints have the following measures.

Tints.				Values.
Violet	-	-	-	7.20
Indigo	-	-	-	8.18
Blue	-	-	-	9.00
Green	-	-	-	9.71
Yellow	-	-	-	10.40
Orange	-	-	-	11.11
Bright red	-	-	-	11.83
Scarlet	-	-	-	12.67

Now the difference of the values for violet and scarlet is 5.47, corresponding to *seven* different colours. Hence, upon the supposition that the eye can distinguish merely these separate colours, the accuracy of the scale is increased in the ratio of 5.47 to 7, that is, from 187 to 239, which gives $3^{\circ}.83$ for the value of each unit.

It is quite manifest, however, that we can distinguish at least three points in the developement of each colour; and even if this could not be accomplished by the unassisted eye, it can readily be effected, to a much greater extent, by crossing the fringe with a standard crystallized plate, and observing the degree of curvature which is produced in the fringes. This standard plate may be shaped like a wedge, so as to exhibit the variation of its tints to a great degree of minuteness. In a wedge of this kind, two inches long, and ground out of a crystallized parallelopiped, so as to have an angle of 8° , the highest tint is between the *blue* and the *white* of the first order, corresponding to 2.20 of the scale, and the lowest tint is between the *black* and the *blue*, corresponding to about 0.8. We have therefore a scale of nearly 2 inches to measure a variation in the tints amounting to $2.20 - 0.80 = 1.40$. The

method of using the wedge or nonius is shown in Fig. 55, (Pl. V.) where AB is the wedge, exhibiting tints which vary in intensity from A to B. If we wish to ascertain the tints of a piece of crystallized glass CD, it must be held as in the figure, and moved from A to B. When it has the position CD, the intersectional figure is open horizontally, which shows that the tints of AB, at the point *m*, are higher than those of CD. In the position GH the figure is open vertically, and therefore the tints of the wedge at *o* are lower than those of the plate. But in the intermediate position EF, a dark cross is produced, which evinces the perfect equality between the tints of the wedge at *n* and those of the plate EF. In this manner all tints may be compared with each other, and referred to the scale of colours.

By forming wedges of crystallized glass in this way, we are enabled to observe the gradations by which the tints pass into each other, and to perform many experiments on the orders of colours, which would otherwise have been impracticable.

The sensibility of the preceding instrument depends on several other causes. 1st. On the intensity of the polarised pencil. 2d. On the transparency of the glass. And 3d. On the removal of all internal reflections at the junction of the plates. In the instrument with 20 plates already mentioned, the glass has a green tinge, and the polarised light suffers no fewer than 40 reflections before it reaches the eye. In order to remove these evils, the light should be polarised by reflection from several of the thinnest and most colourless plates of glass that can be procured, so that each plate may polarise and reflect the light which is transmitted through the plate

Immediately above it. In this way, I have obtained a light as brilliant as that which is reflected from silver. The internal reflections may be removed by interposing a film of oil between each of the plates, so as to rise above that part of the plate where the tint is to be examined.

If the instrument is properly constructed, with these precautions, I have no hesitation in saying, that it will distinctly mark a difference of temperature equal to 1° of FAHRENHEIT'S thermometer.*

I have thus endeavoured to give a brief view of the numerous experiments which have led to the general results unfolded in the preceding enquiry. The length to which this paper has extended, has prevented me from describing many phenomena, and detailing many experiments, which, though interesting in themselves, did not appear absolutely necessary to the establishment of general views.

Had I included in the demonstration of every proposition, the various experimental proofs which I had actually obtained, this Paper would have swelled to a size which would have rendered it unfit for the consideration of the Royal Society; I have, therefore, selected such experiments as appeared most striking, and have left the detail of the rest, and the representation of many of the phenomena, for a separate work which I propose to publish on the subject.†

* This thermometer possesses advantages peculiar to itself, in enabling us to measure the intensity of the heat produced by the friction of any two substances whatever. When glass is one of the substances, the method of employing the instrument is obvious. When any other substance is used, it must be fixed, without cement, to the lower edge of one or more plates of glass, so that its rubbing surface may be as near as possible to the edge of the glass.

† There is one practical result of the preceding experiments, which deserves particular notice. All articles made of glass, whether they are intended for scientific or

I cannot conclude this paper without expressing my obligations to the Rev. Dr. MILNER of Cambridge, for the very handsome manner in which he transmitted to me a quantity of thick plate glass, which I found it impossible to procure from any other quarter. I was thus enabled to obtain several new results, and to complete many experiments that had been left imperfect.*

I have the honour to be, &c.

DAVID BREWSTER.

*To the Right Hon. Sir Joseph Banks, Bart.
G. C. B. P. R. S. &c. &c. &c.*

domestic purposes, should be carefully examined by polarised light before they are purchased. Any irregularity in the annealing, or any imperfections analogous to what workmen call *pins* in pieces of steel, will thus be rendered visible to the eye, by their action upon light. The places marked out by these imperfections, are those where the glass almost always breaks when unequally heated, or when exposed to a slight blow. Hence, glass-cutters would find it of advantage to submit the glass to this examination before it undergoes the operations of grinding and polishing.

* Since the preceding letter was written and sent to Sir JOSEPH BANKS, I have learnt that M. SEEBECK has published in a German Journal for Dec. 1814, an account of some experiments similar to those contained in Sect. II. of this Paper. As there is, so far as I know, only one copy of this Journal in England, in the possession of Dr. THOMSON, I have not been able to obtain a sight of it, in order to compare M. SEEBECK's results with mine. I understand, however, that he has discovered the fact, that a plate of red hot glass often acquires, in cooling, the depolarising structure, and that the tints depend upon the mode of cooling the glass. This result, however, has no connection whatever with the new properties of heat unfolded in the first Section of the preceding Paper, and does not anticipate the developement of the phenomena contained in the Second Section. The discovery of the new property of heat was made by me early in 1814, and an account of it was read before the Royal Society on the 19th of May, 1814. See *Phil. Trans.* 1814, p. 436.

Fig. 1.

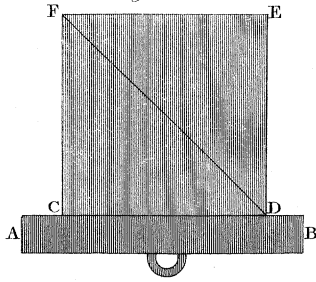


Fig. 2.

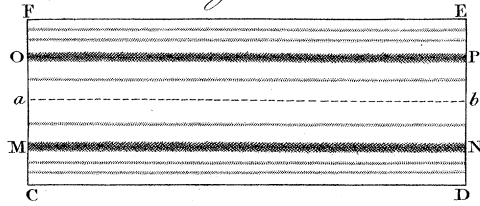


Fig. 3.

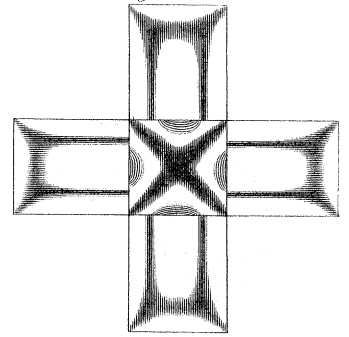


Fig. 4.

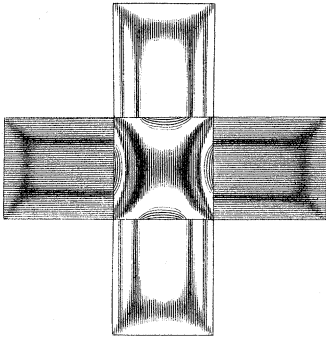


Fig. 5.

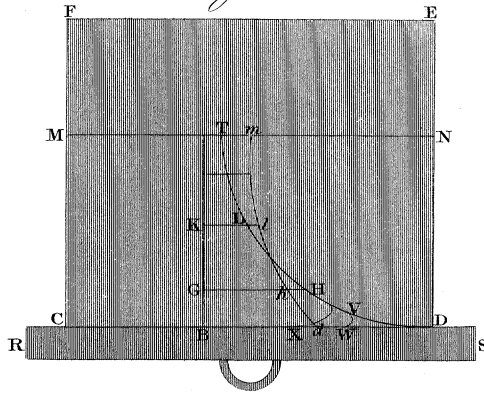


Fig. 6.

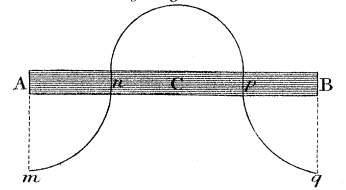


Fig. 7.

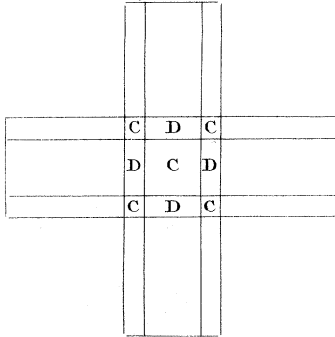


Fig. 8.

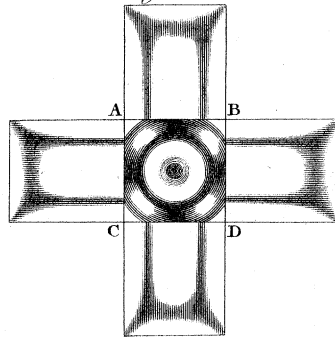


Fig. 9.

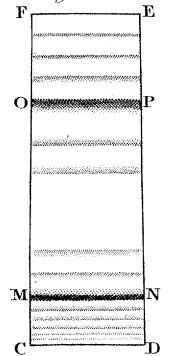


Fig. 10.

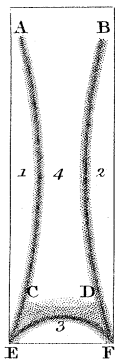


Fig. 11.

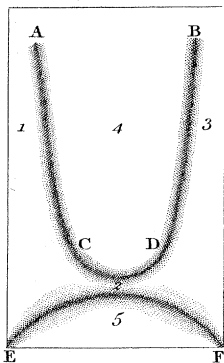


Fig. 12.

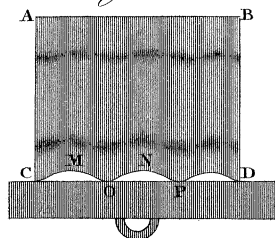


Fig. 13.

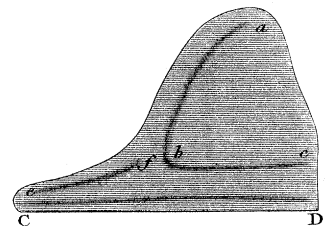


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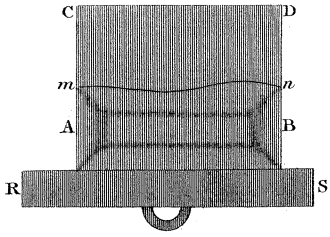


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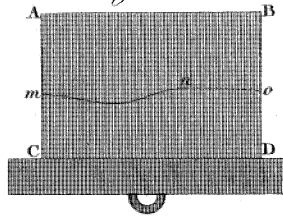


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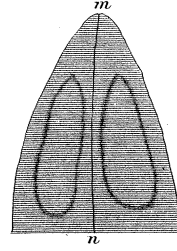


Fig. 17.

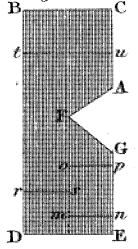


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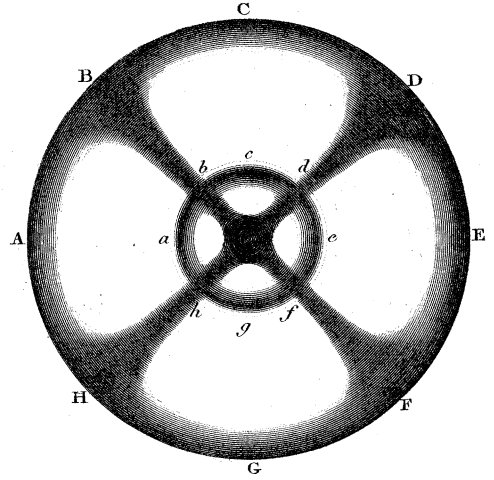


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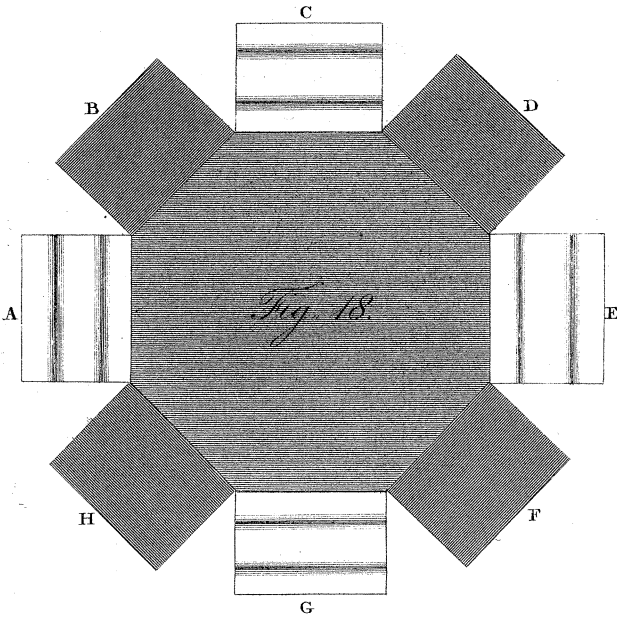


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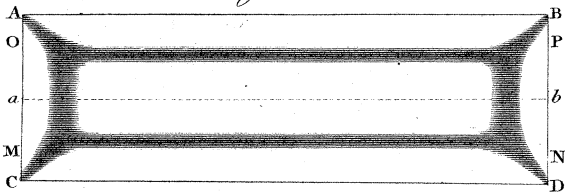


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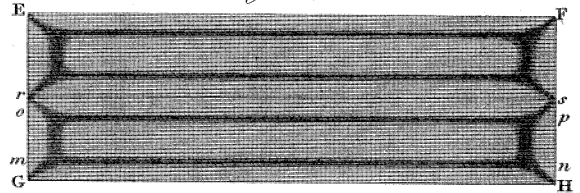


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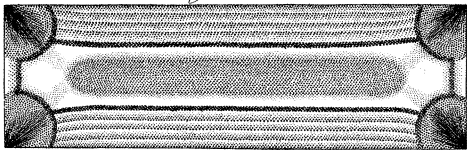


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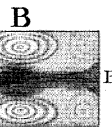


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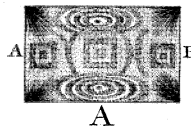


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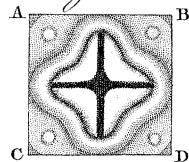


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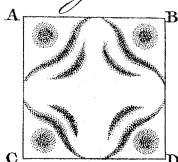


Fig. 27.

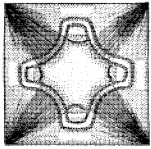


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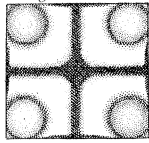


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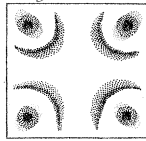


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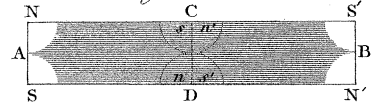


Fig. 28.



Fig. 32.

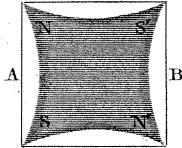


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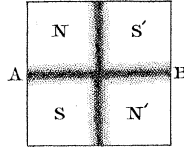


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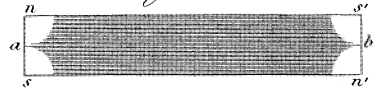


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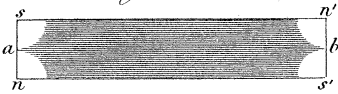


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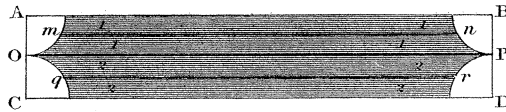


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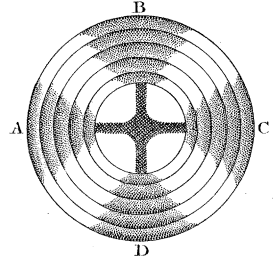


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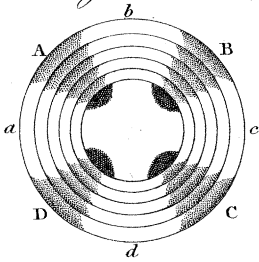


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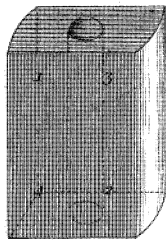


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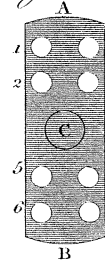


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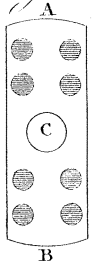


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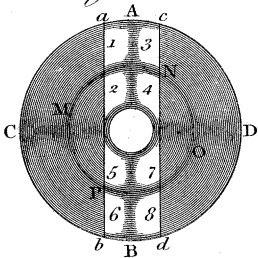


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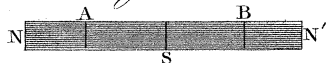


Fig. 44.



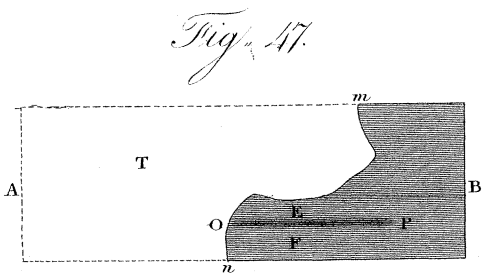
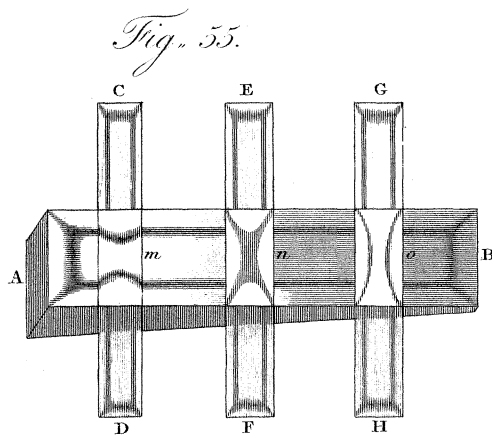
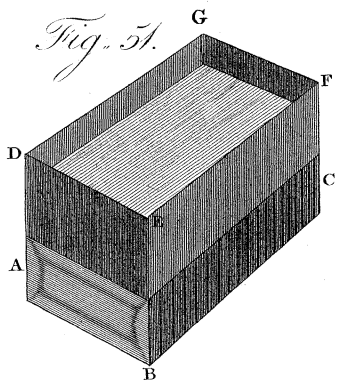
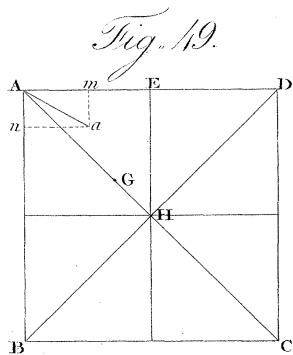
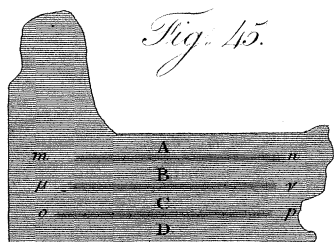


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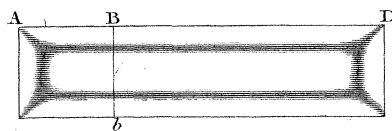


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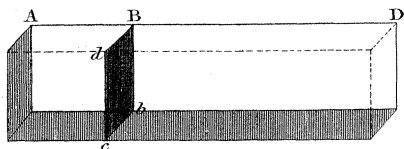


Fig. 50.

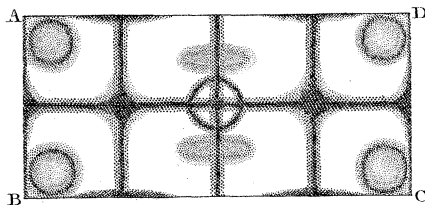


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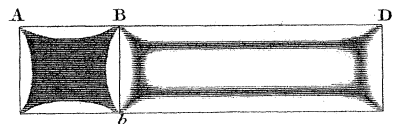


Fig. 48.

