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LXX. *On the Variations which Temperature produces in the Double Refraction of Crystals.* By FREDERICK RUDBERG, Professor of Physics in the University of Upsal\*.

THE researches of M. Mitscherlich having demonstrated that the angles of crystals which do not belong to the regular system, change their magnitude with the temperature, and that the dilatation is consequently different, according to the principal directions of these bodies, or according to their axes of crystallization, there was reason to believe that the double refraction also would vary with the temperature. The existence of this variation was afterwards established by ulterior researches, which M. Mitscherlich, in a manner as simple as it was ingenious, made by the method of interferences, by observing the compensation effected by crossing plates of crystals at different temperatures. By this method, however, we obtain only the ratio between the mean double refraction of the crystal in a cold and in a heated state, without being able to determine how much the refraction of each of the two rays into which the light divides itself, has separately varied with the difference of temperature. In order to decide this question, we must obviously determine directly the refraction at a high temperature; and the following are the results of such an inquiry, made with *rock crystal*, *calcareous spar*, and *arragonite*.

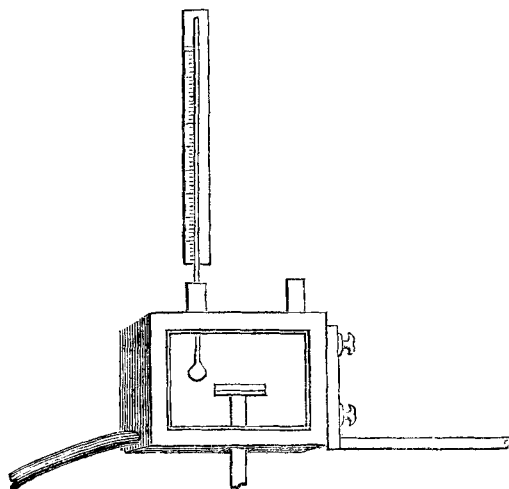
The experiments were made in the same place, and by means of the same instruments and the same prisms, as my former experiments† on the refraction of the same minerals at the temperature of the air; and for this reason I do not

\* Communicated by the Author.

† See our present volume, p. 1, and 136.—EDIT.

here compare them with these. In order to maintain a constant temperature during the whole time that an experiment lasted, it was necessary to have a particular apparatus, of which I shall first give a description.

A box, of the form of a parallelopiped, was made of white iron, and so strong that four of its faces were double, and formed with each other a shut-up space, which communicated only at one side, and beneath one surface, with a small steam boiler; and at the other side, above a second surface, with the external air. The other two surfaces were formed with plates of mica, so that there was an inclosed space which contained only air, and which, when the prism was placed in it, was heated by the steam, which, surrounding the four



sides, circulated only in the space between the four double surfaces, without being permitted to mix with the interior air. The temperature of this space was indicated by a thermometer put into a cork, which was introduced into a tube passing through the two upper surfaces of the box, and which completely closed the tube, in order to prevent the heated air from escaping upwards. A similar tube passing through the two lower surfaces of the box formed a free communication between the interior and the exterior air, so that their elasticity remained always the same. In the middle of this tube, there rose from the centre of the repeating circle a vertical copper rod, carrying on its summit a plate, upon which the crystal was placed. This rod was attached below to another plate of copper, which, instead of

the plate of ground-glass, upon which the prism was placed in my former experiments, rested on the ring of copper, which having teeth upon its circumference could be put in motion by a screw. By this arrangement, which allowed me to turn the prism, it was as easy as formerly, when the prism remained in the open air, to perform all the operations necessary for the exact determination of the refraction, without being obstructed by the heating apparatus, which being on one side united with the boiler by a tube, was on the other side attached to a rod of iron, rising from the masonry on which the repeating circle rested.

The temperature of the interior of the box remained, by this means, perfectly invariable during the time occupied by each experiment. From the temperature, however, of the external air, of which the extremes were on different days  $+12^{\circ}$  and  $+20^{\circ}$ , it varied from day to day between  $+76^{\circ}$  and  $+84^{\circ}$ ; so that there was almost a constant difference of  $64^{\circ}$ .

With respect to the experiments themselves, I ought to remark, that no change in the dispersion could be observed, and that for this reason, I determined the ratio of refraction only for the single ray  $F^*$  of the spectrum. At the beginning of each experiment the prism being at the temperature of the external air, and being turned till the ray  $F$  was at its minimum deviation, the variation in the deviation produced by heating was measured in this position of the prism. For crystals with one optic axis this determination was the only one to be made, because the edge of the prism being parallel to the axis of crystallization, the refracting angle did not change with the temperature. But for crystals with two optic axes, it was necessary, besides this, to determine the change which the difference of temperature produced in the refracting angle, which, as the following results will show, was very considerable.

With respect to the calculation of the index of refraction, it must be observed that the refracting power of the air surrounding the prism being diminished, the deviation becomes at first directly increased, but at the passage of the ray through the last plate of mica, it is, on the contrary, somewhat diminished. These two corrections must be determined separately. According to the experiments of MM. Biot and Arago, the index of refraction of air at  $0^{\circ}$ , and at a barometrical pressure  $= h$ , is

$$= \sqrt{1 + \frac{0.000588767}{1. + 0.00375t} + \frac{h}{0^m.76}}.$$

\* This ray or dark line is nearly the boundary between the *green* and the *blue* space.—EDIT.

The elasticity of the internal and the external air being the same, and almost equal to  $0^{\text{m}}\cdot76$ , we have when  $t$  the mean temperature of the external air is  $+16^{\circ}$ , the index of refraction

$$= \sqrt{1 + 0\cdot000554}, \text{ and}$$

at  $+80^{\circ}$ , or the mean temperature of the internal air, the index will be

$$= \sqrt{1 + 0\cdot0004529}$$

Whence, if  $\nu$  is the ratio between these two elasticities,

$$\nu = 1\cdot000051.$$

If  $\Delta$  is the deviation produced by the prism, and  $\delta\Delta$  the small angle through which the ray deviates still more in passing through the plate of mica, we have

$$\sin \Delta = \nu \cdot \sin (\Delta - \delta\Delta), \text{ or}$$

$$\delta\Delta = \frac{\nu - 1}{\nu} \cdot \text{tang } \Delta$$

which correction ought always to be added to the observed deviation. Calling, in short,  $\pm d\Delta$  the variation produced in the deviation corrected by  $\delta\Delta$ , and putting  $\varepsilon =$  the refracting angle of the prism  $\pm d\varepsilon =$  the variation of this angle, and  $n =$  the index of refraction, we shall have with a sufficient approximation, for crystals with one optic axis,

$$n = \frac{\sin \frac{1}{2} (\Delta \pm d\Delta + \varepsilon)}{\nu \cdot \sin \frac{1}{2} \varepsilon},$$

and for crystals with two optic axes,

$$n = \frac{\sin \frac{1}{2} (\Delta \pm d\Delta + \varepsilon \pm d\varepsilon)}{\nu \cdot \sin \frac{1}{2} (\varepsilon \pm d\varepsilon)}.$$

The results of the observations were as follows:

1. *Calcareous Spar.*—Refracting angle of prism  $= 59^{\circ} 55' 9''$ .

a. *The Ordinary Spectrum.*—For this spectrum I found the remarkable property, *that the crossed wires of the telescope being placed in the ray F, at a low temperature, they always remained fixed there at the highest temperature, notwithstanding a difference of  $64^{\circ}$ .*

The variation which sometimes presented itself during the repetition of the observation was too small to be measured. It is besides evident that the slightest change in the refracting power, would have produced a remarkable change in the deviation, which was  $= 52^{\circ} 53' 43''$ . *This apparent invariability of the deviation proves a small decrease in the refracting power; because if the latter had been perfectly constant, the observation would have shown an augmentation of*

the deviation, for the density of the surrounding air had become less. It is easy to calculate how much this augmentation would have been. The index of the ray F being at the ordinary temperature = 1.66802, the deviation  $\Delta$  calculated by the formula  $\sin \frac{1}{2} (\Delta + \epsilon) = 1.000051 \cdot + 1.66802 \cdot \sin \frac{1}{2} \epsilon$ , becomes =  $52^\circ 54' 14''$ , or greater by  $31''$  than  $52^\circ 53' 43''$ .

From these  $31''$  we must subtract  $\frac{0.000051}{1.000051} \tan 52^\circ 53' = 14''$ ,

or the angle which the ray deviates at the plate of mica, so that there will remain only  $17''$ . Though this quantity is the least which I could directly measure with the repeating circle, I have no reason to believe that if it did occur, it would have escaped me. Whence we may conclude, *that the refractive power of calcareous spar for the ordinary ray, either does not change at all with the temperature, or decreases with it by a quantity extremely small.*

b. *The Extraordinary Spectrum.*—The deviation of the ray F was found to be augmented by a difference of temperature of  $64^\circ$ , a quantity

$$= 2' 26''.$$

If we add to this the correction for the passage of the light

$$\text{through the plate of mica} = \frac{0.000051}{1.000051} \tan 36^\circ 18' 26''$$

=  $8''.0$ , *the total augmentation produced by the temperature in the deviation of the extraordinary ray becomes*

$$= 2' 34''$$

The calculation gives the index = 1.49118, whereas at the ordinary temperature it was = 1.49075. Hence it follows, *that a difference of temperature of  $64^\circ$  produces in the index of refraction of the extraordinary ray of calcareous spar, an increase of +0.00043.*

During my stay at Berlin in the month of May, of the present year (1832), I had fortunately an opportunity of confirming, at the house of M. Mitscherlich, and in his presence, this remarkable property of calcareous spar,—that the deviation of the ordinary ray does not change, at least not in an appreciable manner, with the temperature; while, on the contrary, that of the extraordinary ray increases considerably with the temperature. This property is in a certain manner connected with the discovery of M. Mitscherlich,—that *calcareous spar, when the temperature rises, dilates itself in the direction of the axis of crystallization, but undergoes in a direction perpendicular to the axis a contraction extremely small.* The crystal thus approaches to a cube with an increase of temperature, and the double refraction ought, consequently, to diminish, as

my observations prove. But, on the other hand, it appears singular, that while the dilatation of bodies commonly diminishes their refractive power, the extraordinary ray, though the crystal is dilated in the direction of its axis, becomes nevertheless less refracted, and that the refraction of the ordinary ray, notwithstanding the contraction of the crystal in a direction perpendicular to its axis, does not change, or diminishes if there is any variation. An analogous phenomenon, however, has already been observed by M. Arago in water \*, in which refraction always goes on increasing from the temperature of the maximum density to the point of congelation.

2. *Rock Crystal*.—Refracting angle of the prism =  $45^{\circ} 20' 5''$ . In both spectra a decrease of the deviation was observed, which was also sensibly the same; viz.

$$= 48'' \cdot 0$$

whence, on account of the correction =  $\frac{0 \cdot 000051}{1 \cdot 000051} \tan 28^{\circ} 15'$   
 $= 6'' \cdot 0$ , it follows that the total diminution of the deviations in both spectra is

$$= 42'' \cdot 0.$$

The indices calculated for the ray F become in the extraordinary spectrum =  $1 \cdot 55868$ , or  $0 \cdot 00028$  less than at the ordinary temperature; and in the ordinary spectrum, =  $1 \cdot 54944$ , or  $0 \cdot 00026$  less.

3. *Arragonite*.—The experiments were made with the prisms A, No. 1; A, No. 2; B, No. 2; and C, No. 2.†

In all of them I found for the spectrum polarized perpendicular to the axis of crystallization a diminution, of the deviation produced by an increase of temperature. I also observed a change in the refracting angle of the prisms, with the exception of prism A, No. 1; with which, in this respect, on account of the magnitude of the refracting angle, no experiment with the heating apparatus could be made. The following were the observed results:

	A, No. 1.	A, No. 2.	B, No. 2.	C, No. 2.				
Variation of the deviation . . .	$-5' 8''$	$-1' 53''$	$-4' 3''$	$-2' 58''$				
Variation of re- fracting angle	<table> <tr> <td>not mea- sured.</td> <td><math>+16'' \cdot 0</math></td> <td><math>-1' 53''</math></td> <td><math>-48'' \cdot 6</math></td> </tr> </table>				not mea- sured.	$+16'' \cdot 0$	$-1' 53''$	$-48'' \cdot 6$
not mea- sured.	$+16'' \cdot 0$	$-1' 53''$	$-48'' \cdot 6$					

If we correct these values for the deviation of the plate of mica, we obtain

\* See Edinb. Encyclopædia, Art. EXPANSION, vol. ix. p. 257; and also the observations in the next page.—EDIT.

† See present volume, p. 139.—EDIT.

	A, No. 2.	B, No. 2.	C, No. 2.
Real variation of deviation	-1' 47"	-3' 57"	-2' 52"
Real variation of refract- ing angle . . . . . }	+30"·0	-1' 44"	-40"

Whence we obtain the following indices of refraction:

A, No. 2.	B, No. 2.	C, No. 2.
1·53416	1·69421	1·68976

At the ordinary temperature of the air they were

1·53478	1·69510	1·69058
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Thus the diminutions which an increase of temperature of 64° has produced in the indices of refraction in the spectra polarized perpendicular to the axes of crystallization, are

A.	B.	C.
-0·00062	-0·00089	-0·00082

*The double refraction of arragonite thus appears to decrease a little with the temperature*, because the refracting power in the direction of the axis A has diminished in a smaller ratio than that according to the axes B and C. In other respects arragonite comports itself quite differently from calcareous spar: the axis A of arragonite obviously corresponds with the axis of crystallization of the spar; but notwithstanding this, the refracting power in this direction diminishes in the former, and, on the contrary, increases in the latter; besides that in the direction perpendicular to the axis A, the refracting power diminishes considerably in arragonite, whilst, on the contrary, it undergoes almost no change in Iceland spar.

#### *Observations on the preceding Paper.*

The optical readers of this Journal will, we are sure, join with us in expressing our obligations to Professor Rudberg, for the accurate and valuable observations contained in the preceding communication, which he has been so kind as to transmit to us. The subject is entirely new, and we trust that he will extend his researches to other minerals, and also to artificial salts. The influence of heat in modifying the refractive power of uncrystallized solids, such as glass, gums, &c.; of fluids, such as water, oil, &c.; of fluids with circular polarization, such as oil of turpentine, &c.; and of minerals, &c. belonging to the tessular system, such as rock salt, alum, &c.—merit the attention of Professor Rudberg.

In reference to the important observation of M. Arago, that the refractive power of water gradually increases while it passes from that of its maximum density to that of congelation, we beg leave to quote the following observations\*.

“When the writer of this article had the pleasure of seeing

\* Art. EXPANSION, Edinb. Encyclopædia, vol. ix. p. 257.



M. Arago at Paris, in the course of last summer (1814), he mentioned to him a series of experiments on the refractive power of water at different temperatures, in order to determine if its maximum density was above  $32^{\circ}$ . He filled a prism with water at the temperature of  $32^{\circ}$ , and observed the angle of deviation produced by refraction, while its temperature rose from  $32^{\circ}$  to  $212^{\circ}$ . The angle of deviation was greatest at  $32^{\circ}$ , and it gradually diminished to  $212^{\circ}$ , exhibiting no marks whatever of a variation of refractive power at  $40^{\circ}$ , or at any point between  $32^{\circ}$  and  $212^{\circ}$ . Hence M. Arago concluded, that since the refractive power always increases with the density, the density of water must be a maximum at  $32^{\circ}$ . \* \* \* It is assumed in this reasoning, *that the refractive power of bodies increases with their density*,—a doctrine which requires to be established by direct experiment, before it can be admitted as a valid argument in favour of any other position. Nay, it has actually been proved by Albert Euler, from numerous experiments, that the refractive power of glass is *increased by heat*. An augmentation of temperature of  $60^{\circ}$  of Reaumur diminished the focal length  $\frac{1}{63}$ th part, and an augmentation of  $33^{\circ}$  produced a diminution of  $\frac{1}{97}$ th. M. Euler concludes, without sufficient evidence, that the refractive power of fluids is increased with heat."

Looking at all these facts together, the action of heat is very anomalous :

Heat increases the refractive power of glass.

Heat diminishes the refractive power of water, oils, &c.

Heat increases the extraordinary refractive power of calcareous spar.

Heat diminishes the extraordinary refractive power of quartz.

Heat does not affect the ordinary refractive power of calcareous spar.

Heat diminishes the ordinary refractive power of quartz.

Hence there is reason to infer that heat produces some other change in the state of a body than a mere change in the relative distance of its particles.

The difference between the action of heat on *calcareous spar* and *quartz* is very extraordinary. The primitive form of each is a rhomb; and they differ only in the former having *negative*, and the latter *positive* double refraction. It will, therefore, be of importance to examine other negative and positive crystals; and if the difference of effect is not found to depend upon this circumstance, it may possibly arise from the peculiar structure of quartz in reference to circular polarization.

Among the other crystals which M. Rudberg will doubtless examine, we trust he will not omit *sulphate of lime* and *glauberite*, on the doubly refracting structure of which, heat produces such extraordinary effects.—D. B.

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LXXI. *On the Action of Heat in changing the Number and Nature of the Optical or resultant Axes of Glauberite.* By SIR DAVID BREWSTER, K.H. LL.D. F.R.S. V.P.R.S. Ed.

SEVERAL years ago Prof. Mitscherlich made the beautiful discovery, "that the ordinary *sulphate of lime* or *gypsum* which, at common temperatures, has two optic axes in the plane of its laminae inclined at  $60^\circ$  to each other, undergoes a great change by elevation of temperature; the axes gradually approaching each other, collapsing into one, and (when yet further heated) actually opening out again in a plane at right angles to the laminae."

Sir John Herschel, in whose words we have described this remarkable experiment, goes on to observe, "This singular result we cite from memory, having in vain searched for the original source of our information; but it might have been expected, from the low temperature at which the chemical constitution of this crystal is subverted by the disengagement of its water, that the changes in its optical relations by heat would be much more striking than in more indestructible bodies. We have not, at this moment, an opportunity of fully verifying the fact; but we observe that the tints developed by a plate of sulphate of lime, now before us, exposed as usual to polarized light, rise rapidly in the scale when the plate is moderately warmed by the heat of a candle held at some distance below it, and sink again when the heat is withdrawn, which, so far as it goes, is in conformity with the result above stated. Mica, on the contrary, similarly treated, undergoes no apparent change in the position of its axes or in the size of its rings, though heated nearly to ignition\*."

In repeating this important experiment, I made use of one of the specimens described in the Phil. Trans. for 1818, in which I discovered one of the resultant axes of this mineral. It was about  $1\frac{1}{2}$  inch thick in the plane of the laminae, and the system of rings which surrounded this axis was exceedingly minute, with the usual black brush at each end of them. The other system of rings could not be seen in this specimen, owing to the manner in which it was cut. Having brought the crystal to a considerable heat, and exposed it to polarized light, it

\* Treatise on Light, Encyclop. Metrop. p. 568.