II. *On the Laws which regulate the Absorption of polarised light by Doubly Refracting Crystals. 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.*

Read November 12, 1818.

My Dear Sir,

In examining the polarising structure of acetate of copper, my attention was drawn to certain changes of colour which this crystal exhibited when exposed in different positions to polarised light. As this variation of colour was independent of the thickness of the plate, and of any analysis of the transmitted pencil, I had no hesitation in regarding it as a new affection of light, and in ascribing the phenomenon to the absorption of the homogeneous tints which formed the compound colour of the crystal. I therefore collected all the natural and artificial crystals which were characterized by any peculiarity of colour, and examined the various phenomena which they presented, when cut at different angles with the axis, and when exposed in different positions to a polarised ray. The results which I obtained during this investigation were singular and unexpected, and I am persuaded will throw considerable light on that property of transparent bodies, by which they detain and assimilate to their own substance a portion of the rays which penetrate them, while the rest are freely and copiously transmitted. As this faculty of absorbing light is related to the axes of double refraction, I

The Royal Society is collaborating with JSTOR to digitize, preserve, and extend access to *Philosophical Transactions of the Royal Society of London.* www.jstor.org

shall first describe the phenomena which are presented by crystals with One axis, and then explain the modifications which these phenomena undergo when the number of axes is increased.

SECT. I. *On the absorption of polarised light by Crystals with One axis of double refraction.*

If we fasten upon one side of a rhomboid of *colourless calcareous spar,* a circular aperture of such a magnitude that the two images of it appear distinctly separated when viewed through the spar, we shall find, by exposing it perpendicularly to common light, that the two images are perfectly colourless, and of the same intensity in every position of the rhomboid. Hence if Q be the quantity of transmitted light, we shall have the ordinary image $O = \frac{1}{2} Q$, and the extraordinary image $E = \frac{1}{2} Q$.

When the rhomboid is exposed to polarised light, the intensities of the images vary with the azimuthal angle (a) which the axis of the rhomboid forms with the plane of primitive polarisation, and may be represented by the formulæ $O = Q \cos.^2 a$; $E = Q \sin.^2 a$. But since $Q \cos.^2 a + Q \sin.^2 a = Q$ we have $O + E = Q$; that is, the sum of the intensities of the two pencils is in every position equal to the whole transmitted light, and therefore the rays which leave any one of the images by a change of azimuth, are neither reflected nor absorbed, but *pass over into the other image.* The ordinary phenomena of double refraction, consequently, afford us no reason for conjecturing that the crystals which possess this property absorb the incident light in any other way than is done by all other bodies, whether solid or fluid.

If we now take a rhomboid of certain specimens of *yellow calcareous spar*, and perform with it the experiments which have just been described, we shall obtain a series of entirely different results. The two images will now be found to differ both in colour and intensity, the extraordinary image having an orange yellow hue, while the colour of the ordinary image is a yellowish white. This difference of colour is distinctly related to the axis of the crystal, and increases with the inclination of the refracted ray to the short diagonal of the rhomb. It is a maximum in the equator, while along the axis the two images have exactly the same colour and intensity. In every position, however, the combined tints of the two images are exactly the same as the natural tint of the mineral. In comparing the intensities of the two images, the extraordinary one appears always the faintest, so that there is an interchange of rays; and while the extraordinary force carries off several of the yellow rays from the ordinary image O, the ordinary force at the same time takes to itself several of the white rays from the extraordinary image E; for if this were not the case, the extraordinary image would always have the greatest intensity, whereas, in consequence of its exchanging yellow for white light, it becomes actually fainter than the ordinary image.

If we call m and n the maximum number of rays which the extraordinary and the ordinary image interchange, and (φ) the inclination of the refracted ray to the axis, the intensities may be represented by the following formulæ when the crystal is exposed to common light. $O = \frac{1}{2} Q + \sin.^2 \varphi\, m - \sin^2 \varphi\, n$ and $E = \frac{1}{2} Q + \sin.^2 \varphi\, n - \sin.^2 \varphi\, m$. The values of m and n vary in different crystals: they are always of different colours, and in some cases they are equal to nearly one half of the transmitted light,

When the rhomboid is exposed to polarised light, a series of still more interesting phenomena is exhibited. In the position where O vanishes, E is an *orange yellow*, exactly the same as it appeared by common light; and in the position where E vanishes, O is a *yellowish white*, as before. Now it is obvious, that in the first of these positions the image E was not strengthened by the white light of the vanished image O, otherwise the image E would have had the same colour as $O + E$, or the natural tint of the spar; and that in the second position, the image O had not received the whole of the vanished image E, otherwise it would have had the tint expressed by $O + E$. It therefore necessarily follows, that a portion of the pencil O has been absorbed in the first position, and a portion of the pencil E in the second. The quantity of light absorbed is a maximum in the two positions where a is 0° and 90°, and is equal to the quantities m and n, which the two images interchange. At different angles with the axis, therefore, it is measured by $\sin.^2 \varphi\, m$, $\sin.^2 \varphi\, n$. When this angle is given, the absorbed light varies with the azimuthal angle a, and may be found from the following formula, viz. $T = O \cos.^2 a + E \sin.^2 a$, which supposes that m and n are equal to E and O. Hence when $a = 0°$ $T = O$, or the whole of the pencil E is absorbed. When $a = 45°$, $T = \frac{1}{2} O + \frac{1}{2} E$, or one half of O and E is absorbed, and when $a = 90°$, $T = E$, or the whole of the pencil O is absorbed. When the absorbing crystal is viewed by a doubly refracting prism, the tints of the two pencils Pe and Po will be given by the formulæ $Pe = O \cos.^2 a + E \sin^2. a$, and $Po = E \cos.^2 a + O \sin._2 a$.

The property which I have now described as belonging to Calcareous spar, I have found in other twelve crystals with *One axis.* The colour of the ordinary and extraordinary images, or of the absorbed pencils *m* and *n*, is shown in the following table.

List of Absorbing Crystals with One Axis.

Names of Crystals.	Colour when its axis is in the plane of primitive polarisation.	Colour when its axis is perpendicular to that plane.
Zircon	Brownish white	A deeper Brown
Sapphire	Yellowish green	Blue
Ruby	Pale yellow	Bright pink
Emerald	Yellowish green	Bluish green
Emerald	Bluish green	Yellowish green
Beryl blue	Bluish white	Blue
Beryl green	Whitish	Bluish green
Beryl yell. green	Pale yellow	Pale green
Rock crystal, almost transparent	Whitish	Faint brown
Rock crystal yell.	Yellowish white	Yellow
Amethyst	Blue	Pink
Amethyst	Greyish white	Ruby red
Amethyst	Reddish yellow	Ruby red
Tourmaline	Greenish white	Bluish green
Rubellite	Reddish white	Faint red
Idocrase	Yellow	Green
Mellite	Yellow	Bluish white
Phosp. of lime (lilac)	Bluish	Reddish
———————— olive	Bluish green	Yellowish green
Phosphate of lead	Bright green	Orange yellow
Calcareous spar	Orange yellow	Yellowish white

The property which these crystals possess of absorbing the different tints in different positions of the axis, with regard to the plane of primitive polarisation, does not belong to every specimen. There are many crystals of ruby, sapphire, emerald, &c. which give an ordinary and an extraordinary image of the same colour; and whenever this is the case, they are destitute of the property of absorbing polarised light. These two classes of phenomena are indeed invariably connected, and will ultimately be found to have the same origin.

The extreme generality of this property is indicated by the number of crystals in the preceding table, which embraces all the coloured crystals which are at present known to have only one axis of double refraction, excepting *titanite*, *molybdate of lead*, *carbonate of iron and lime*, *arseniate of copper*, certain specimens of *sulphate of nickel*, and *super-acetate* of *copper and lime*, in which I have not detected the property of absorbing polarised light.*

The various coloured minerals which have the cube, the regular octohedron, and the rhomboidal dodecahedron for their primitive form,† are, as might have been expected, destitute of the property of absorption; and I have not been able to discover it in differently coloured glasses, that have received the polarising structure from rapid cooling, or from mechanical compression, or dilatation.

Some of the preceding crystals, such as the *Sapphire* and the *Idocrase* exhibit different colours when common light is transmitted in directions parallel and perpendicular to their axis of double refraction. A specimen of *sapphire* had a *deep blue colour* in one direction, and a *yellowish green* in the opposite direction; and several specimens of *idocrase* had an

---

* See the *Phil. Trans.* for 1818, p. 211.

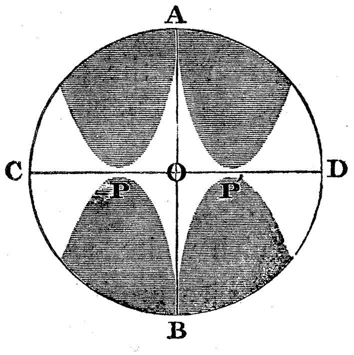
† *Id.* p. 254.

orange yellow tint along their axis, and a *yellowish green* tint in a direction perpendicular to their axis. The exhibition of two colours in the same mineral by common light, was first seen in *Iolite*, and the Abbé Haüy had the boldness to give it the name of *Dichroite* from this property, on the presumption that nature had limited it to this mineral. This *dichroism*, as it may be called, which, so far as I know, has never been observed in any other minerals than iolite and mica, is a very common property of crystallized bodies, as will be seen from the following section.

Sect. II. *On the absorption of polarised light by crystals with two axes of double refraction.*

The general phenomena of absorption in crystals with two axes, are nearly the same as those which have been described in the preceding section; but the quantity of light which the ordinary and extraordinary forces interchange, is regulated by new laws depending on the situation of the incident ray with respect to the two axes of double refraction.

If O*o* and AB, a line perpendicular to it, are the two axes, and P,P′, the resultant axes, or the poles of no-polarisation of *Blue Topaz:* then if COD, the plane of the resultant axes is perpendicular to the plane of primitive polarisation, the polarised light incident on the plate at O will be *blue* after transmission. The blue tint preserves its intensity from O to A and B, the thickness of the plate being supposed to continue the same; but as the incident ray



passes from O to C and D, its intensity diminishes gradually, the light becoming more and more white with a slight tinge of red, till it reaches C and D, where it has the same colour as that of the topaz in common light. As the plate of topaz is turned round the polarised ray, the blue tint changes into white, according to the law given in the preceding section, excepting in the line CD, where the tint is invariably white in every azimuth. When the polarised light is transmitted along any of the resultant axes P, P′, the two tints diverge from the poles in the form of a cross, as shown in the preceding figure.

The effect at O, or the interchange of the blue and white light between the ordinary and extraordinary rays, is related to the axis AB alone; and in like manner the effect at A is related solely to the other axis O. But though the axis O*o* is more powerful in topaz than AB, yet the values of *m* and *n* for each axis do not appear to be different; a result which might have been expected from the fact, that these tints in different crystals have no relation to the intensity of their polarising forces. The diminution of the tints *m* and *n*, in passing from O to C and D, is owing to the action of the other axis O. At the points C and D blue light alone will be transmitted when AB, considered as a separate axis, is perpendicular to the plane of primitive polarisation; and at the same point white light alone will be transmitted when O considered as a separate axis of the same character is similarly placed. Hence it follows, that the transmitted light should be bluish white, as it actually is, the interchanged portions being as it were in a state of equilibrium.

The following table contains the tints *m* and *n* in several crystals, in which the effect will be seen in every azimuth.

List of absorbing Crystals with Two axes.

	Plane of the resultant axes in the plane of prim. polarisation.	Plane of the resultant axes perpendicular to the plane of prim. polarisation.
Topaz blue	White	Blue
—— green	White	Green
—— greyish blue	Reddish grey	Blue
—— pink	Pink	White
—— pink yellow	Pink	Yellow
—— yellow	Yellowish white	Orange
Sulphate of barytes		
—— yellowish purple	Lemon yellow	Purple
—— yellow	Lemon yellow	Yellowish white
—— orange yellow	Gamboge yellow	Yellowish white
Kyainte	White	Blue
Dichroite	Blue	Yellowish white
Cymophane	Yellowish white	Yellowish
Epidote olive green	Brown	Sap green
—— whitish gr.	Pink white	Yellowish white
Mica	Reddish brown	Reddish white

The following table shows the characters of *m* and *n* in crystals with two axes, which I have not been able to examine in every azimuth.

	Axis of prism in the plane of primitive polarisation.	Axis of prism perpendicular to the plane of primitive polarisation.
Mica	Blood red	Pale greenish yellow
Acetate of copper	Blue	Greenish yellow
Muriate of copper*	Greenish white	Blue
Olivine	Bluish green	Greenish yellow
Sphene	Yellow	Bluish

---

* The tints are given in relation to the short diagonal of its rhomboidal base.

	Axis of prism in the plane of primitive polarisation.	Axis of prism perpendicular to the plane of primitive polarisation.
Nitrate of copper	Bluish white	Blue
Chromate of lead	Orange	Blood red
Staurotide	Brownish red	Yellowish white
Augite	Blood red	Bright green
Anhydrite	Bright pink	Pale yellow
Axinite	Reddish white	Yellowish white
Diallage	Brownish white	White
Sulphur	Yellow	Deeper yellow
Sulphate of strontites	Blue	Bluish white
———— cobalt	Pink	Brick red
Olivine	Brown	Brownish white

In the last eight crystals of the preceding table the tints are not given in relation to any fixed line.

The following table contains the characters of *m* and *n* in crystals, the number of whose axes I have not yet determined.

Phosphate of iron	Fine blue*	Bluish white
Actinolite	Green	Greenish white
Precious opal	Yellow	Lighter yellow
Serpentine	Dark green	Lighter green
Asbestos	Greenish	Yellowish
Blue carb. of copper	Violet blue	Greenish blue
Octohedrite	Whitish brown	Yellowish brown

Several of the preceding crystals which have a laminated structure, such as mica, epidote,&c. or such as have an imperfect transparency from a defective aggregation of their elementary crystals, frequently exhibit their absorptive qualities, and

---

* When the axis of the prism was in the plane of primitive polarisation.

also their system of coloured rings, by exposure to common light. The light is, in these cases, analyzed in passing obliquely through the laminæ, in the same manner as if it had been transmitted through a bundle of glass plates.

I shall now conclude this section with a particular account of some very interesting phenomena exhibited by several crystals in the preceding tables.

1. *Super-acetate of copper.* When a prism of this metallic salt is exposed to the solar rays, so that the plane of refraction is perpendicular to the axis of the rhomboidal prism, and the ray passes through the angle of the rhomboid, which is 70°, two distinct images of the sun will be observed; and the one which has suffered the greatest refraction will be *greenish yellow*, while the other will be of a *deep blue* colour. This separation of the two tints is more distinct in some prisms than in others, owing to the manner in which they are cut from the rhomboidal crystal, and in certain points of incidence the two images have the same tint. When a plate of super-acetate of copper is ground so thin as to be transparent, it has a brilliant green colour, composed of blue and greenish yellow. If it is exposed to polarised light, so that the axis of the rhomboidal prism is in the plane of primitive polarisation, the *greenish yellow* light will be entirely absorbed, and the transmitted ray will be of a *deep blue* colour. By turning the plate round the polarised ray, the greenish yellow rays will re-appear, and will gradually regain their former intensity; while the blue rays will in the same proportion be absorbed, till after one-fourth of a revolution the transmitted light will be wholly *greenish yellow*. When the faces of the plate are perpendicular to any of the two resul-

tant axes of the crystal, the blue and the greenish yellow light have the form of a cross, the branches of which diverge from the two poles of no-polarisation.

2. *Augite.* When a plate of yellowish brown augite was exposed vertically to common light, the transmitted pencil had a moderate intensity; when it was inclined to one side, in the plane of one of its neutral axes, the light became more and more intense as the obliquity increased, notwithstanding the increase of thickness in the direction of the ray. By examining the light with a prism of calcareous spar, it was found to be all polarised in a plane perpendicular to the plane of inclination. When the plate was now inclined, from this last position in the opposite direction, the intensity of the light gradually diminished till the plate became absolutely impervious to the strong rays of the sun. The pencil which had formerly vanished when the light was analyzed by Iceland spar, now re-appeared, and gradually increased, becoming more and more *green*, while the other pencil, which became fainter, grew more and more *red*, till at a very great obliquity the one pencil became *perfectly green*, and the other a *deep blood red*. By exposure to strong polarised light, the *red* and the *green* were alternately absorbed, according to the position of the neutral axis with respect to the plane of primitive polarisation.

2. *Dichroite* or *Iolite*. This curious mineral has been long known to exhibit by common light a *deep blue* colour along the axis of the prism, and a *faint yellow* or grey colour in a direction perpendicular to it. I have ascertained that these two colours are those of its ordinary and extraordinary images; and even when seen by common light, that they are

related to its axes of double refraction. Dichroite has two axes of extraordinary refraction, the two resultant axes being inclined 62° 50′ to each other, or 31° 25′ to the axis of the prism. If we cut a plate of dichroite with four parallel faces, each of which is perpendicular to the resultant axes, and is inclined 31° 25′ to the axis of the prism, and expose it either to common or to polarised light, so as to have the plane of its resultant axes perpendicular to the plane of primitive polarisation, we shall observe the branches of blue and white light diverging in a beautiful manner from its poles P, P′. (See the figure in p. 17, which is a very imperfect representation of the phenomenon.) The white light becomes more blue from P and P′ to O, and more yellow from P and P′ to C and D. When the plane of the resultant axes is in the plane of primitive polarisation, the poles P, P′ are marked by spots of white light, but every where else the tint is a deep blue. In the plane CADB, the mineral when seen by common light is yellow mixed with a small quantity of blue, polarised in an opposite plane. From A and B towards P and P′, the yellow image becomes fainter till it changes into blue, and the weak blue image is reinforced by other blue rays till the intensity of the two blue images is nearly equal. The faint blue image increases in intensity as the incident ray approaches from C and D to P and P′. From P and P′ to O one of the images is whitish, and the other deep blue, but the whiteness gradually diminishes towards O, where they are both equally blue.*

---

* Two crystals of Dichroite which I directed to be cut so as to exhibit these phenomena, are in the cabinet of Thomas Allan, Esq. to whose friendship I have been indebted for several of the minerals noticed in this paper.

4. *Epidote.* The cross formed at the resultant axes of epidote has its diverging branches *brown* and *sap green,* and they are distinctly seen in common as well as in polarised light. The green shades into a pale greenish white as the ray recedes from P and P′ to C and D, where it is no longer divisible into two differently coloured pencils. At O the two pencils are brown and green, and at A and B they are brown and a paler green. The dichroism of the epidote is distinctly marked in common light. Along the axis of the prism, and through two of its parallel faces, its colour is a deep orange, while through the other two parallel faces it is a yellowish green.

5. *Mica.* A specimen of this mineral exhibits the branches diverging from P and P′ exactly in the same manner, whether it is seen by common light, or exposed to a polarised ray with the plane of the resultant axes perpendicular to the plane of primitive polarisation. In these positions the branches PA, PB, &c. are a dark brown, and PC, PO, &c. a brownish white. When the plane of the resultant axes is in the plane of primitive polarisation, the colours of the branches are interchanged. The dichroism of mica is finely exhibited in some of its small and perfect crystals. In some of these its colour by common light is greenish yellow along the axis of the prism, and of a deep garnet colour when the light is transmitted through its faces.

6. *Anhydrite.* This mineral exhibits its dichroism by common light. When the light is transmitted in a direction parallel to the laminæ, its colour is pink; but when it is incident in a direction perpendicular to the laminæ, its colour is a palish yellow slightly tinged with pink.

SECT. III. *On the influence of heat in modifying the absorbent power of crystals.*

Having selected several crystals of *Brazilian topaz*, which displayed no change of colour by exposure to polarised light, I found, that after bringing them to a red heat, or even boiling them in olive oil or in mercury, they experienced such a change in their structure, as to exhibit distinctly the power of absorbing polarised light. I next took a topaz, which had one of its two pencils yellow, and the other pink. By exposing it to a red heat, the heat acted more powerfully upon the extraordinary than upon the ordinary pencil, discharging the yellow colour entirely from the one, and producing but a slight change upon the pink colour of the other.

In the formation of pink topazes by heat, it has always been supposed, that the yellow colour is actually changed into pink; but this is quite a mistake, for the pink colour must previously exist in a state of combination with the yellow, and must either form the colour or exist in the colour of one of the pencils produced by double refraction. The heat does no more than discharge one colour, and leave the other almost unimpaired. This result is of considerable practical importance to the jeweller, as it enables him to determine before hand, whether or not any topaz will receive a pink colour from heat; for if this colour exists in one of its images, which will in general be seen by exposing it to a polarised ray, he may predict with certainty the success of his experiment.

When a topaz possessing a pink tint has been taken from the fire, it is at first perfectly colourless, and acquires the pink colour gradually in the act of cooling. By exposing it repeatedly to the action of a very intense heat, I have never been able either to remove or to modify this permanent tint.

With the view of ascertaining if the absorbing structure could be induced by heat, I exposed to a white heat several crystals of yellowish calcareous spar. After the action of the fire had been continued for some time, a sort of opalescence, or milky opacity, was induced; and the light, which went to the formation of the ordinary image, was much redder than that which formed the extraordinary ray. This effect I naturally ascribed to some change in the state of the carbonic acid; and upon continuing the action of the heat, and watching the process of decomposition, I found that when the carbonic acid was expelled from a film about the 200th part of an inch thick, its surface was covered with *vesicles arranged in straight lines parallel to the short diagonal of the rhomboid.* These vesicles had, in general, an elliptical form, with a cut or opening in the direction of their transverse axis through which the gas had escaped. After the spar was taken from the fire, a great number of the vesicles burst with a noise similar to that which accompanies the bursting of the indusium of the fern, and carried off a portion of the thin calcareous pellicle. When this pellicle was removed, the subjacent surface was covered with a series of minute parallel grooves inclined about 20° 57′ to the short diagonal. In repeating this experiment, and seizing the proper time for withdrawing the spar from the fire, I have never failed to observe the fact of the arrangement and bursting of the vesicles, and I have no hesitation in concluding, that the carbonic acid is arranged in planes passing through the axis of the crystal, a result which I had formerly assumed in explaining the phenomena of double refraction. This method of studying the structure of bodies by watching them in the process of disintegration, may be found to have a very extensive application in chemical and mineralogical enquiries.

The observations contained in the preceding pages, indicate in a manner by no means equivocal, that the colouring particles of crystals, instead of being indiscriminately dispersed throughout their mass, have an arrangement related to the ordinary and extraordinary forces which they exert upon light. In some specimens the extraordinary medium is tinged with the same colouring particles, and with the same number of them as the ordinary medium : but in other specimens of the same mineral, the extraordinary medium is either tinged with a different number of particles of the same colour, or with a colouring matter entirely different from that of the ordinary medium. In certain specimens of topaz, the colouring matter of the one medium is more easily discharged than that of the other ; and in two specimens of *emerald*, the colouring matter which tinges the ordinary medium in the one, tinges the extraordinary medium in the other, and *vice versa.*

All those crystals in which the colouring matter of the one medium differs either in character or intensity, possess the property of absorbing the two tints according to the laws already mentioned, but there is also reason to believe, that polarised light suffers the same kind of absorption in those crystals whose two images have the same tint, and even in those which are perfectly colourless.

I have the honour to be, &c.

DAVID BREWSTER.

Edinburgh, Oct. 17th, 1818.

To the Right Hon. Sir Joseph Banks, Bart. G. C. B. &c. &c. &c.