Note on the double refraction of compressed glass

by Augustin Fresnel
(read 16 September 1822)

with analytical table of contents
by the editors of Fresnel's *Oeuvres complètes*
1866–70

Translated and annotated by Gavin R. Putland*
Version 1, April 21, 2021

English translation of A. Fresnel, "Note sur la double réfraction du verre comprimé", *Annales de Chimie et de Physique*, Ser. 2, vol. 20, pp. 376–83 (1822), as reprinted in *Oeuvres complètes d'Augustin Fresnel*, vol. 1 (1866), pp. 713–18, with the corresponding extract from the "Table Analytique" in *Oeuvres complètes...*, vol. 3 (1870), at p. 595.

Brewster has discovered that when a plate of glass between two polarizers is compressed or stretched in a single direction, it displays colors analogous to those of birefringent crystalline plates, whence he has promptly concluded that stress induces birefringence. As not all physicists were convinced that such colors were due to simple birefringence, Fresnel, in 1819, established by interference experiments that the propagation speed depends on whether the polarization is parallel or perpendicular to the compression. Although Fresnel himself was thereby convinced of the birefringence, he has thought it desirable to confirm the conclusion through actual double refraction.

Four right-angled isosceles glass prisms were lined up with their long rectangular faces touching end-to-end in the same plane, and with their 90° refracting angles facing the same way. The spaces between were filled by three more prisms with the same base dimensions but a slightly shorter height; and two half-prisms, also of reduced height, were added at the ends so as to make the overall assembly rectangular. To suppress reflections, the residual air gaps were filled with turpentine with a refractive index nearly equal to that of the glass. When the first-mentioned prisms were compressed in a suitably designed vise (the others escaping the compression by being shorter), objects viewed through the length of the assembly appeared double, the two images having a separation of about 1.5 mm at one metre, with polarizations parallel and perpendicular to the direction of compression.

Fresnel confidently expects that compression in two perpendicular directions to different degrees would produce biaxial birefringence, and that the inclinations of the optic axes would be easily calculable from the strains; but he acknowledges that experimental verification would be difficult because of the almost inevitable non-uniformity of compression.

Returning to the experiment just reported, he concludes with the daring prediction that if the stressed glass prisms are replaced by unstressed quartz prisms with their optical axes along the length of the assembly, there will again be two images, which will appear unpolarized when viewed through an analyzer but, when viewed through a Fresnel rhomb (as we now call it), will be polarized at ±45° to the plane of reflection of the rhomb.

— *Translator*.

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Translator's preface

The manuscript of this "Note" is dated 8 September 1822 — that is, 20 days after Fresnel's work on biaxial double refraction was received with acclaim by the Academy of Sciences, and 19 days after the successful test of the eight-panel Fresnel lens destined for Cordouan Lighthouse. According to its long title in Fresnel's *Oeuvres complètes* [10, vol. 1, p. 713], the paper was read to the Academy on 16 September (as confirmed by the *Procès-verbaux* [1] for that date). The subtitle then notes its publication in *Annales de Chimie et de Physique*,[1] and in the *Bulletin de la Société philomathique* for 1822 (from p. 139). But the footnote to the title adds:

> (a) Only the text printed in the *Annales* is complete. That of the *Bulletin de la Société philomathique* lacks the last three paragraphs and is not accompanied by the figure.

It continues:

> The Note is intimately linked to the theoretical concepts supporting the general theory of double refraction. We thought however that we should place it here, because it is the immediate development of the last paragraph of No. XXV, and because Fresnel alludes to it at the beginning of Nos. XXVII and XXVIII.

The three references are respectively [10, p. 712], [8], and [9].

Footnotes to the present translation are mine, although the last of them reports a corresponding footnote by the editors of the *Oeuvres complètes*. Items in *square brackets*, in the main text or the analytical table, and including citations such as "[7, pp. 505–8]", are also mine. Unusually, there are no footnotes by Fresnel himself, and the editors have not added section numbers. The original French text gives Brewster and Young the title "M." Here I have given them their usual English titles.

— *Translator*.

Analytical Table of Contents

[1] In the issue nominally for August 1822, which did not actually appear until the second week of October [1, p. 372].

Dr. Brewster first recognized that by compressing glass, one could give it the property of coloring polarized light; and having assured himself, by a series of important experiments, that the coloring phenomena of a glass plate compressed or stretched in a single direction were altogether similar to those presented by crystalline plates endowed with double refraction,[2] he did not hesitate to venture that the compression or stretching of glass gave it the structure of doubly refractive crystals.[3]

To suppose that the glass in this case receives a crystalline structure, even an imperfect one, is in my view a rash hypothesis; it does not seem probable to me that the corresponding faces of the smallest particles of glass would be more parallel to each other during compression than before; the only general change that would be quite certain is a greater proximity of the molecules in the direction of compression than in the perpendicular directions.

As to the existence of double refraction in compressed glass, some very able physicists had not considered Dr. Brewster's experiments as sufficient proof of the bifurcation of the light, and they thought that the glass thus modified could present the polarization phenomena of doubly refractive crystals without necessarily possessing all their other optical properties.

In the hypothesis of mobile polarization,[4] the double refraction of compressed glass is not a necessary consequence of the coloration phenomena that it presents, notwithstanding their perfect resemblance to those of crystalline plates; but, when it is admitted that the latter come from the mutual influence of the rays that have traversed the crystalline plate with different speeds, as Dr. Young was the first to show,[5] it becomes almost indispensable to admit also that the coloration phenomena of compressed glass likewise result from a small path difference between the luminous rays that pass through it—that is, in a word, that it enjoys double refraction.

Although I would long since have adopted this opinion, it did not seem to me so well demonstrated that one should neglect the experimental verifications that might offer themselves; this is what prompted me, in 1819, to ensure that light actually passes through compressed glass with two different speeds, by the very precise methods afforded by diffraction and the principle of interference. I recognized that the light actually passed through the same plate of glass with more or less speed according as the incident beam was polarized parallel or perpendicular to the axis of compression,[6] and I even measured the difference for various degrees of condensation and dilatation of the glass in a bent plate. I confess that after having done these experiments, there remained for me no more doubt on the existence of double refraction in compressed glass and the angular separation of the light into two distinct beams, when it penetrates the glass at an oblique incidence; for this bifurcation is a necessary mechanical consequence of the two speeds of propagation of light in the same medium, whether one adopts the theory of waves or that of emission.

Nevertheless it seemed to me interesting to produce two images with compressed glass, in order to complete the proofs of its double refraction and make it perceptible to the eyes of physicists who would not have the same confidence in interference methods, or who, not adopting any hypothesis on the mechanical causes of refraction, would not regard the bifurcation of light as a necessary consequence of the existence of its two speeds. This was a new opportunity to show the infallibility of the principle of interference and the correctness of the consequences deduced from it.

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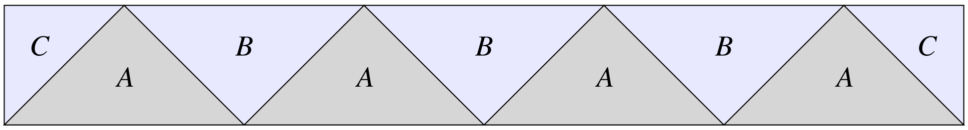
2 Fresnel's explanation of these phenomena is found in [4].

3 Brewster, 1815 [2] and 1816 [3].

4 See, e.g., the translator's preface to [5].

5 *Quarterly Review*, London, April 1814, reprinted in [11] at pp. 266–72.

6 As the plane of polarization is perpendicular to Fresnel's direction of vibration (which in modern terms is the direction of the electric displacement **D**), Fresnel is saying that propagation is slower if the vibration is in the direction of compression (consistent with a higher permittivity in that direction).



As the double refraction of glass compressed, even to breaking point, is very weak, a single prism would have given only a barely perceptible divergence, even if its refracting angle had been very obtuse; that is why I have employed four prisms A, A, A, A. The refracting angle of each of them is a right angle; they are placed one beside the other, with the refracting angles turned to the same side, and the opposite bases supported on the same plane and brought close to each other so that they touch each other by their longitudinal edges. It is in the direction of these edges that the prisms are compressed between two iron jaws, with the aid of four screws which press a steel plate covered by a blade of wood and a sheet of cardboard; the other ends of the prisms also rest against one of the jaws of this sort of vise, via a sheet of cardboard and a blade of wood, so that the glass is pressed more evenly and does not break so easily: the screws have their nuts and take their support points in the other jaw of the vise.

To achromatize these four prisms and suppress deviations in the light path that are useless to the experiment, I have interposed three reversed prisms B, B, B, likewise having a 90° refracting angle, and placed at the ends of the apparatus two prisms C, C, of 45° only, so as to recompose a rectangular parallelepiped of glass, which the rays traverse almost in a straight line and perpendicular to its two extreme faces. In order that the rays can pass from one prism to the other, the nine prisms are glued together with turpentine [French: *térébenthine*], whose refractive power is nearly equal to that of the Saint-Gobain crown[7] employed in this experiment, so that the light is but little attenuated by the partial reflections at the surfaces of passage.

The three 90° prisms B, B, B, and the two 45° half-prisms C, C, all of which serve to achromatize the four compressed prisms A, A, A, A, are a little shorter than these, and therefore cannot suffer any pressure. One can imagine that, if they had been pressed like the others and to the same degree, they would have canceled the effect of the first, since their angles are turned in the contrary direction, while the small divergences between the ordinary and extraordinary beams produced by them are added successively to each other because their refracting angles are turned to the same side.

The axis of double refraction of glass compressed in a single direction must be the direction of the compression itself, as Dr. Brewster has judiciously observed. Now, in a medium of a single axis, it is always perpendicular to this axis that the difference in speed of the ordinary and extraordinary rays is greatest, and that one can consequently obtain the most appreciable divergences: this is why I pressed the prisms in the direction of their longitudinal edges, perpendicular to the direction in which the light traverses them. Thus I obtained, by a strong compression, double images whose spacing was a millimetre and a half, at a distance of one metre.

One might fear that this separation of the light into two beams needed only some striae in the glasses, but, by changing the position of the eye, it is easily recognized that this is not such an effect: admittedly one sees a variation of the spacing of the images, which arises from the fact that the prisms are not compressed to the same degree throughout; but, to a trained eye, these variations cannot be confused with the effects presented by striae. Besides, which cuts through all difficulty, one of the images is polarized parallel to the axis of compression, and the other according to a perpendicular plane.

In accordance with my idea of the mechanical causes of double refraction, I believe that all the optical properties of crystals of one axis should be reproducible by compressing or stretching the glass in a single direction, and those of crystals of two axes by compressing or stretching it in two perpendicular directions and to different degrees. So to explain clearly the modification that I suppose to be imparted to this substance, let us consider a cube of class whose particles, initially located at equal distances from each other, in the three directions perpendicular to the faces of the cube, are then brought a little closer by compression along two of these directions. If these compressions are equal, we shall return to the case of crystals of a single axis; but if they are unequal, the medium will present three different spacings

[7] Fresnel names the glass type "crown" in English.

of its molecules, in the three rectangular directions, and must possess all the optical properties of crystals of two axes. The inclinations of the two optic axes, relative to these three rectangular directions, will be easily calculable from the degrees of shortening that we impart to the dimensions of the cube. I have not yet tried to check these indications of the theory by experiment, which seems difficult because of the almost inevitable inequalities of pressure on the different points of the same glass surface. Nevertheless, with suitable precautions, perhaps we shall succeed in obtaining some approximate checks. In that case I am confident that we shall find the facts in conformity with the results of the calculation.

Before undertaking these experiments, and as soon as my occupations permit, I propose to use a pile of prisms analogous to that which I have just described, to study the double refraction of rays that pass through quartz along the axis of crystallization. It will be necessary to place side-by-side four or five quartz prisms with their refracting angles turned to the same side, and achromatized by crown prisms glued together with turpentine; the entry and exit faces of each crystal prism will be equally inclined to the axis, and their relative inclinations from one prism to the other will need to be such that light rays which have traversed the first prism parallel to its axis will also traverse all the others parallel to their axes. The two images thus obtained will present a very peculiar phenomenon: instead of being polarized like all those that result from double refractions hitherto observed, they will show the characteristics of direct light when we look at them through a rhomb of calcite; but they will differ from it in that, if we make them undergo two total reflections in a parallelepiped of glass,[8] with an interior incidence of about 50°, they will find themselves polarized according to two perpendicular planes, each inclined at 45° to the plane of reflection.[9]

I have thought it possible to announce these results in advance (at least as very probable), because of the striking and numerous similarities between the phenomena of coloration of quartz plates [with faces] perpendicular to the axis, and those that I have obtained by placing a thin crystalline plate, [with faces] parallel to the axis, between two glass parallelepipeds[10] crossed at right angles, in which the polarized light, both before and after its passage through the crystalline plate, suffers two total reflections in the planes inclined at 45° to the principal section thereof. These singular phenomena have been described and calculated in two Memoirs, which I had the honor of presenting to the Academy towards the end of the year 1817 [6, p. 460, note 2] and at the beginning of 1818 [7, pp. 505–8].[11]

Paris, 8 September 1822.

A. Fresnel.

[8] That is, a Fresnel rhomb.

[9] In the terminology to be introduced in Fresnel's next memoir [9], they will be *circularly polarized* in opposite directions.

[10] Fresnel rhombs.

[11] Cited as Nos. XVI and XVII in a footnote in the *Oeuvres complètes* [10, vol. 1, p. 718*n*].

References

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[2] D. Brewster, "On the effects of simple pressure in producing that species of crystallization which forms two oppositely polarised images, and exhibits the complementary colours by polarised light", *Philosophical Transactions of the Royal Society*, vol. 105, pp. 60–64, read 19 Jan. 1815; doi.org/10.1098/rstl.1815.0006.

[3] D. Brewster, "On the communication of the structure of doubly refracting crystals to glass, muriate of soda, fluor spar, and other substances, by mechanical compression and dilatation", *Philosophical Transactions of the Royal Society*, vol. 106, pp. 156–78 (with two plates), read 29 Feb. 1816; doi.org/10.1098/rstl.1816.0011.

[4] A. Fresnel, "Note sur le calcul des teintes que la polarisation développe dans les lames cristallisées" et seq., *Annales de Chimie et de Physique*, Ser. 2, vol. 17, pp. 102–11 (May 1821), 167–96 (June 1821), 312–15 ("Postscript", July 1821); reprinted (adding section nos.) in [10], vol. 1, pp. 609–48; translated by G.R. Putland as "On the calculation of the tints that polarization develops in crystalline plates, & postscript", doi.org/10.5281/zenodo.4058004 (2021).

[5] A. Fresnel, "Note sur les remarques de M. Biot, publiées dans le cahier précédent", *Annales de Chimie et de Physique*, Ser. 2, vol. 17, pp. 393–403 (August 1821); reprinted (adding section nos.) in [10], vol. 1, pp. 601–608; translated by G.R. Putland as "Note on the remarks of Mr. Biot relating to colors of thin plates", doi.org/10.5281/zenodo.4541332 (2021).

[6] A. Fresnel, "Mémoire sur les modifications que la réflexion imprime à la lumière polarisée" ("Memoir on the modifications that reflection impresses on polarized light"), signed & submitted 10 Nov. 1817, read 24 Nov. 1817, printed in [10], vol. 1, pp. 441–85.

[7] A. Fresnel, "Supplément au Mémoire sur les modifications que la réflexion imprime à la lumière polarisée" ("Supplement to the Memoir on the modifications that reflection impresses on polarized light"), signed 15 Jan. 1818, submitted 19 Jan. 1818, printed in [10], vol. 1, pp. 487–508.

[8] A. Fresnel, "Extrait d'un Mémoire sur la double réfraction particulière que présente le cristal de roche dans la direction de son axe" ("Summary of a Memoir [9] on the peculiar double refraction presented by quartz in the direction of its axis"), *Bulletin de la Société philomathique* for 1822, pp. 191–8; reprinted in [10], vol. 1, pp. 719–29.

[9] A. Fresnel, "Mémoire sur la double réfraction que les rayons lumineux éprouvent en traversant les aiguilles de cristal de roche suivant les directions parallèles à l'axe" ("Memoir on the double refraction that light rays undergo in traversing the needles of quartz in directions parallel to the axis"), 9 Dec. 1822, printed in [10], vol. 1, pp. 731–51.

[10] A. Fresnel (ed. H. de Sénarmont, E. Verdet, & L. Fresnel), *Oeuvres complètes d'Augustin Fresnel* (3 vols.), Paris: Imprimerie Impériale, 1866, 1868, 1870.

[11] T. Young (ed. G. Peacock), *Miscellaneous Works of the late Thomas Young, M.D., F.R.S., &c.*, vol. I, London: J. Murray, 1855; archive.org/details/miscellaneouswo01youngoog.