CHARACTERISTICS OF STRIÆ IN OPTICAL GLASS

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I. APPEARANCE AND EFFECTS OF STRIÆ

In the manufacture of optical glass one of the difficult requirements, perhaps the most difficult that the manufacturer has to meet, is that the glass shall be homogeneous. Glass which

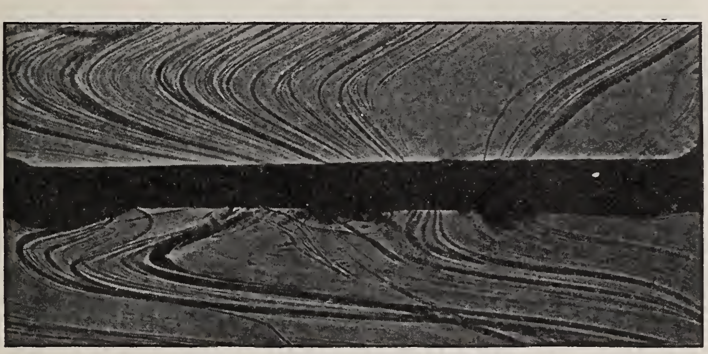

FIG. 1.—*Shadowgraph of heavy striæ*

has been melted and stirred with the utmost care will contain bubbles and striæ. The latter, sometimes called "cords" or "veins," consist usually of threads or sheets of material of which the refractive index is a little different from that of the surrounding glass. There results from this difference in index an irregularity in the wave front of the light traveling through the glass. Sometimes the irregularities are sufficiently great for a casual glance to reveal that there are striæ in the glass, but with optical glass that has passed the first rough inspection a rather careful examination is needed to detect their presence. Figs. 1 and 2 are photographs showing the appearance, much accentuated, of several gradations of striæ in slabs picked for the purpose. Both plates of Fig. 1 possess heavy striæ which would be observed at a casual glance even by an unpracticed eye. The striæ of the plates in Fig. 2 would be classed as light, those in the upper piece being particularly light. A careful visual examination would enable one to see the striæ in the lower plate of Fig. 2, but it is doubtful whether the striæ in the upper one could be detected by such observation.

There are highly sensitive methods for detecting the presence of striæ, but there seems to be no unanimity of opinion as to how much damage to any given optical system may be done by the presence of a given stria or nest of striæ. It was for the purpose of obtaining some information on this question that this investigation was undertaken.

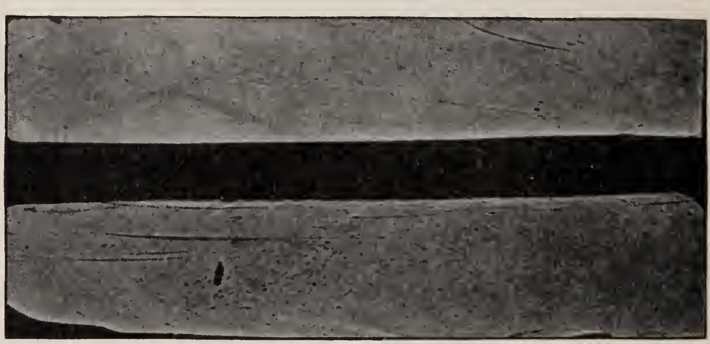

Fig. 2.—*Shadowgraph of light striæ*

1. DETECTION OF STRIÆ

Very coarse striæ can be seen by a casual inspection, even in the rough fragments as they come from the pot. For the detection of finer striæ it is necessary that either two opposite faces of a slab be polished or that the slab be immersed in a liquid having very nearly the index of refraction of the glass. In testing at the glass factory, which has been operated in Pittsburgh by this Bureau since 1917, a mixture of carbon bisulphide and gasoline has been used with success for this purpose.

For a simple inspection it is easier to have the glass polished on opposite faces, in which case the glass can be held about 2 feet from the eye and the striæ seen by passing the glass across the line of sight to the edge or to some crosspiece of a window frame. With a little practice surprising skill can be developed in this method of testing, and not long ago one of the manufac-

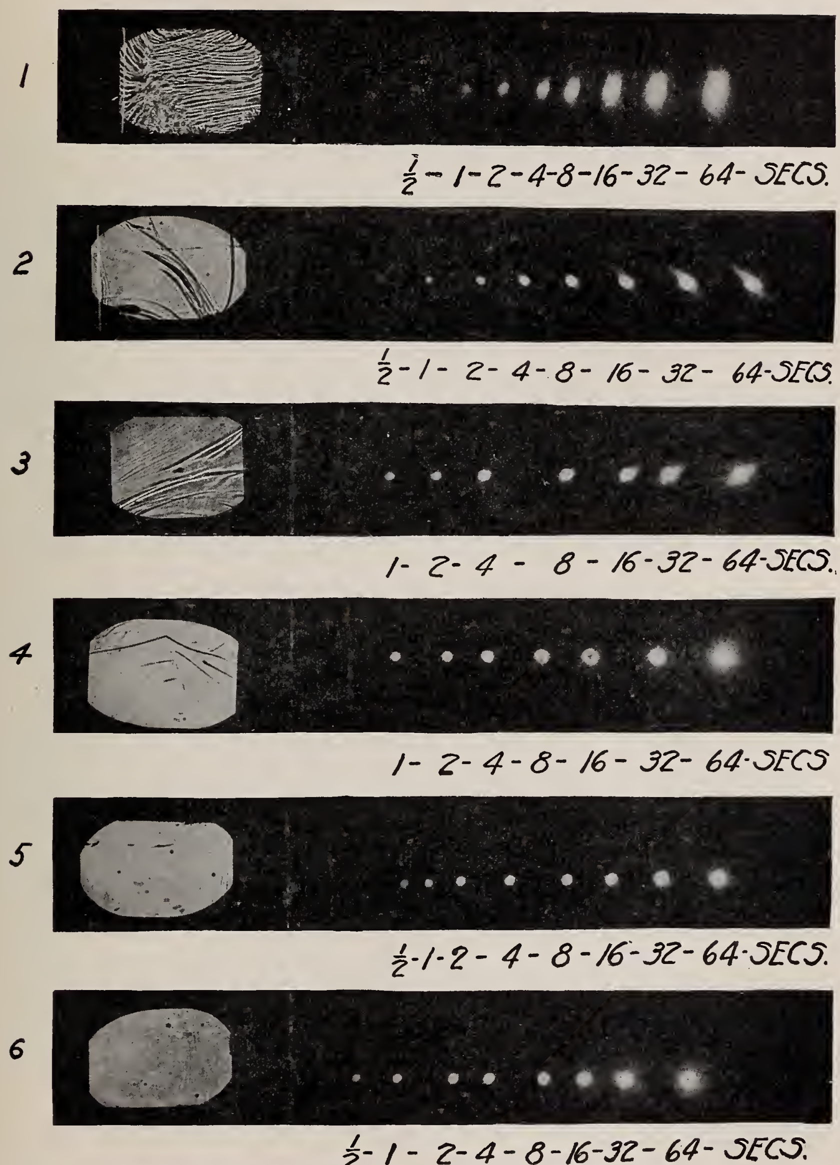

FIG. 3.—*Striated prisms and their corresponding star images*

turers of glass was confining himself to it. For the more general uses striæ which are heavy enough to be injurious can undoubtedly be detected in this way.

A little refinement in the operation consists in placing an auxiliary lens of perhaps 8 to 10 inches focal length between the eye and the glass. If a fairly small source—an incandescent light 10 or 15 feet off answers very well—be used at some distance from the observer, and if the light pass through the slab and the lens in succession and the eye pupil be placed at the image of the source, the striæ in the glass will be easily visible. Of course striæ in the lens will show up likewise, but a rotation of the lens enables the observer to distinguish between lens and plate. If the refinement of this apparatus be carried one step farther and

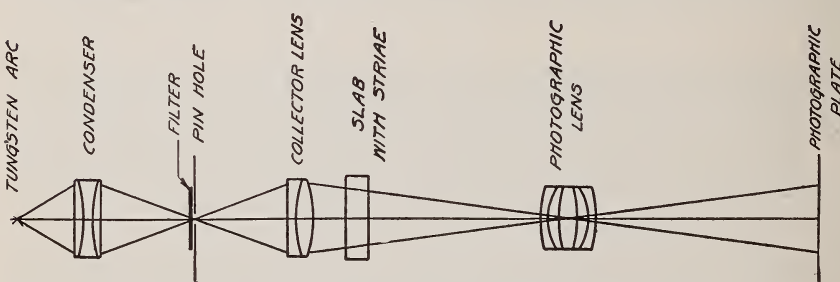

FIG. 4.—*Projection of the striæ in a flat slab of optical glass*

The plate is placed a short distance "out of focus" for the image of the slab

an artificial star with a collimator be substituted for the incandescent light, an apparatus is obtained which will probably detect all striæ which could ever have an injurious effect in any optical instrument.

It is possible to carry the refinement another step farther, using a knife-edge or small opaque disk to hide the image of the star, in which case only the light that is deviated by the striæ reaches the eye, whence greater contrast is obtained.[1]

2. PROJECTION OF STRIÆ

In order to get a record of striæ, it is necessary to project them upon a photographic plate, a result which can be reached in a number of ways.

POLISHED SLABS OR PRISMS need simply to be placed between a white screen and a strong, approximately a point, source of light in order to have a shadow of the striæ appear on the screen.

[1] In testing with an immersion tank it is very convenient to use a second pinhole in place of the opaque disk, for in that case the position of the image of the pinhole is fixed. With a slab having polished faces, any angle between these faces refracts the images with consequent inconvenience to the observer.

The photographs of the six prisms shown in Fig. 3 were taken in this way.

The results of the projection can be rendered somewhat more striking by using a projection lens, as in Fig. 4. The two photographs of Figs. 5 and 6 show the results so obtained. If the glass be so set that its image is sharply in focus on the photo-

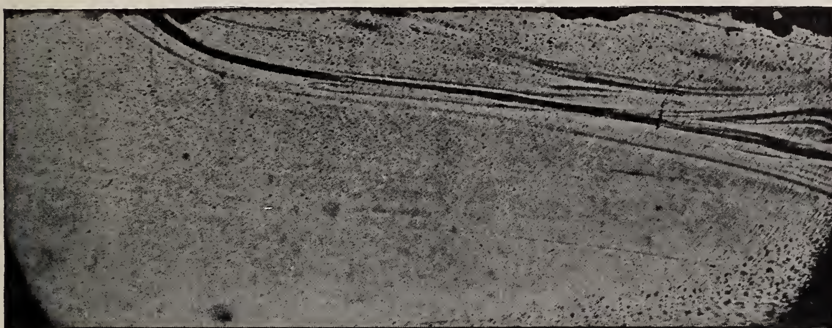

FIG. 5.—*Striæ in slab too close to projection lens for best focus*

graphic plate, the striæ are very faint; but if the image be thrown a little out of focus, the striæ show up clearly. The slab of glass was moved a little too close to the projection lens for good focus in Fig. 5 and was a little too far away for good focus in Fig. 6, the slab being moved about 7 cm. between the two exposures. A stria which appears dark with the projection screen on one

FIG. 6.—*Striæ in slab of Fig. 5 too far from projection lens for best focus*

side of the focus will appear bright when this screen is moved to the other side of the focus. This change in the appearance of the image here shown is characteristic. By this means it is always possible to distinguish between a scratch or a bubble and a stria.

The striæ in the slab photographed in Figs. 5 and 6 are prominent and are readily seen with the unaided eye.

A set-up of essentially the same type as that shown in Fig. 4 was devised by Dr. S. M. Burka of this Bureau in collaboration with Dr. M. Zwillinger of the optical shop annex of the Naval Gun Factory at Rochester, and has been used for routine testing of binocular prisms, one girl testing several hundred in a day with very little eyestrain.

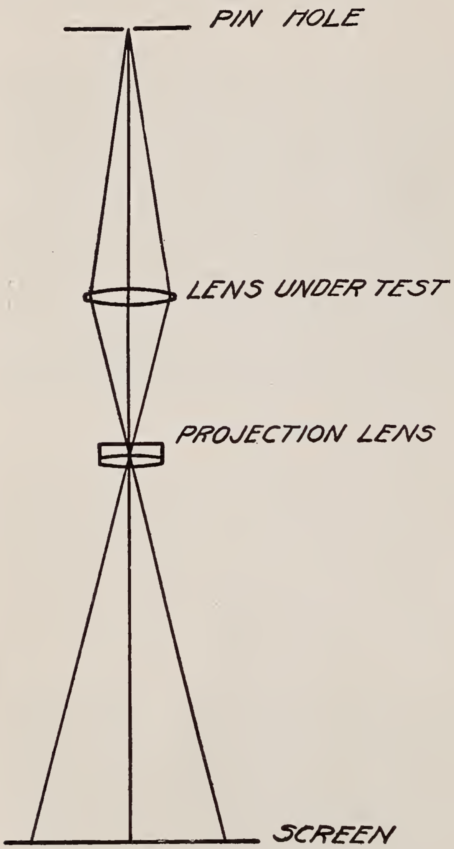

FIG. 7.—*Projection of the striæ in a lens*

The distances must be adjusted to suit the focal length of the lenses. A collimating lens may be used if it be desired to pass a plane wave through the lens

THE STRIÆ IN A LENS can be detected by simply catching their shadow on a diffusing screen placed between the lens and the focus of a near-point source, the sun, for example, if the striæ are at all heavy. They may be more conveniently projected with the aid of an auxiliary lens and a suitable optical train, as shown in Fig. 7, although almost any device which with a near-point source of light would give an out-of-focus image of the lens would be suitable. A photograph of the striæ in the crown component of a binocular objective is shown in Fig. 8. For a telescope the arrangement shown in Fig. 7 has given very good results, a screen or a photographic plate being placed outside of the image formed of the point source by the auxiliary lens, which does not need to be particularly good. A binocular objective or even a simple lens of about the same focal length serves very well.

A photograph of the striæ in the two barrels of a binocular is shown in Fig. 9. This was obtained by catching the light on a photographic plate after passage through the telescope from a near-point source.

3. CHARACTERISTIC STRIÆ

The striæ of Figs. 1 and 2 are typical of the sort which result when glass is melted, stirred, cooled, broken out, then reheated, paddled, and molded. The heaviness of the striæ is determined by factors which are beyond the scope of this paper; but the striæ consist usually of veins or cords which vary greatly in prominence and density. In some cases they are light and scattered, as in Fig. 2 and in the lower prisms of Fig. 3, while in others they are heavy and prominent, as in Fig. 1, or may be densely packed, like tubes of vermicelli, as with the upper prism of Fig. 3.

Fig. 8.—*Striæ in binocular objective*

At times it has seemed desirable to roll optical glass into plates in the same way in which ordinary plate glass is rolled, and in such cases the ordinary cords or veins are pressed out into sheets parallel to the faces of the rolled plate. Fig. 10 shows the striæ in two such plates, the one exhibiting the heavier striæ being a piece of ordinary green-colored window plate glass with rectangular faces, about three-fourths of an inch thick and polished on two opposite faces (2 inches apart). The second is a piece of clear-rolled, dense flint, $N_D = 1.616$, from the Bausch & Lomb Optical Co., given to Mr. Smith by Maj. F. E. Wright, of the Army Ordnance Bureau. The striæ in the dense flint, though very distinct in the photograph, are, in fact, very light and can be seen with only the greatest difficulty by the unaided eye. The appearance of the window plate, when viewed perpendicularly to the faces, is shown in Fig. 11; the markings are, so far as we could tell, entirely surface irregularities. This plate, set at 45° to the line of projection, gave as a result Fig. 12, which again does not show the striæ of Fig. 10. In fact, sheet striæ of this sort are not visible when they lie even at angles of a few degrees, possibly 5 or 6°, to the line of projection. A right-angled

Fig. 9.—*Striæ in the two barrels of a binocular*

prism made out of glass similar to the dense flint of Fig. 10, but having heavier isolated striæ, was placed in the path of an intense beam and a shadow of the striæ thrown on a screen, in which case a slight rotation of the prism made the shadow of the striæ almost invisible.

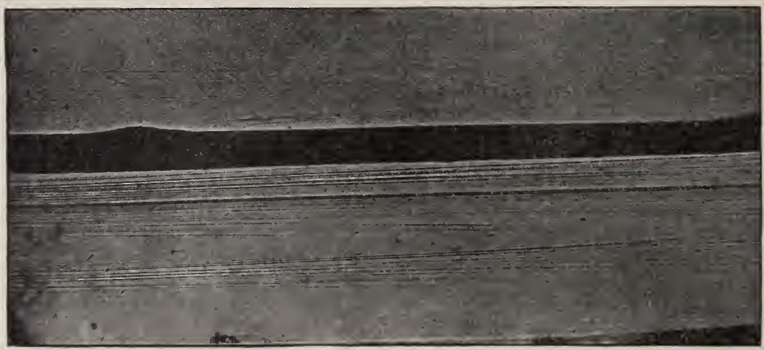

FIG. 10.—*Top: Rolled dense flint viewed edgewise. Bottom: Rolled window glass viewed edgewise*

Figs. 13 and 14 show the striæ in a rolled plate through polished edges and through the polished faces, respectively. This is clear-white, rolled crown glass, and shows very clearly that for glass of this sort an examination through the flat faces offers no criterion as to the quality of the glass, unless it is to be used with the line of sight perpendicular to the faces.

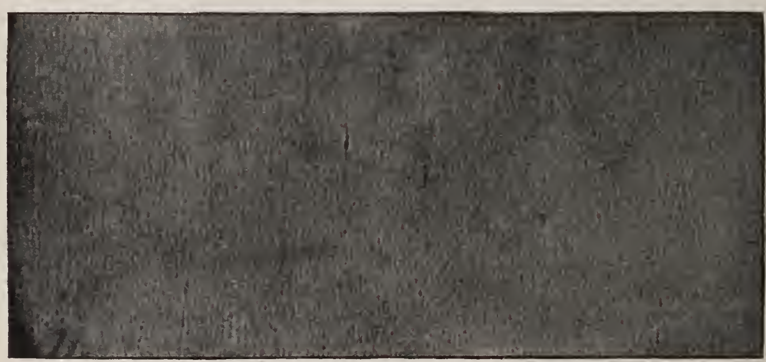

FIG. 11.—*Rolled window plate of Fig. 10 viewed flatwise*

4. STRIÆ AND DEFINITION

The effect of striæ upon definition of an image produced by an optical system in which they are present is an important question, to which it is difficult to give a definite answer. In general, it is obvious that striæ which are sufficiently heavy and dense will injure the definition, and a mere glance edgewise through the window plate of Fig. 10 or through the plate of Fig. 13, at a straight edge, makes it evident that such irregular refraction as is exhibited by these plates seriously blurs the image. The effect of such striæ is shown in Fig. 15, which presents images of an artificial star, as seen first without (*a*) and then with the plate interposed.

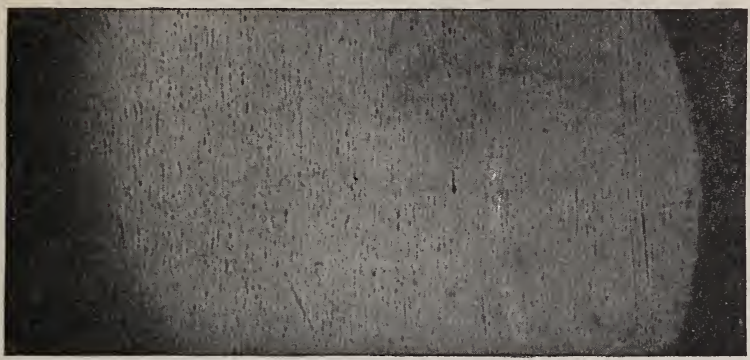

Fig. 12.—*Rolled window plate of Fig. 10 viewed at an angle of 45°*

The images (*b*, *c*) seen through the flat of the window plate are very little inferior to those obtained with a clear aperture, whereas the images (*d*, *e*, *f*), viewed through the polished edges, are blurred on account of the pronounced scattering of the light.

That dense striæ are seriously injurious to definition is then evident. However, there are many good lenses which contain a

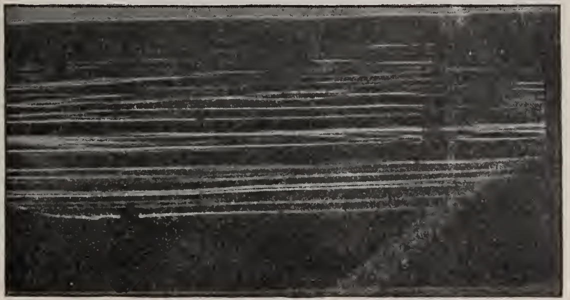

Fig. 13.—*Rolled crown glass viewed edgewise*

few isolated striæ, and a few isolated striæ do very little damage. So much is this true that an examination of a large number of rejected binoculars at this Bureau showed no certain connection between the presence of striæ and faults of definition. The striæ in a large, high-grade photographic lens are shown in Fig. 16, and the striæ in a telescopic lens with an aperture of about 5 inches and a focal length of about 20 inches are shown in Fig. 17. This lens was made from Bureau glass and finished by John Clacey in the optical shop. The definition and performance are excellent.

That the presence of even a considerable amount of not too heavy striæ is not greatly injurious to the definition in ordinary

FIG. 14.—*Sample of Fig. 13 viewed flatwise*

use may be seen from the photograph (Fig. 9) of the striæ in a six-power binocular, which was among those submitted by the Signal Corps of the United States Army to this Bureau for test. The striæ in the left barrel of this binocular are prominent. There was an observable amount of scattered light about the image of an artificial star when an auxiliary telescope was used, but without such an aid the images produced by both barrels were equally

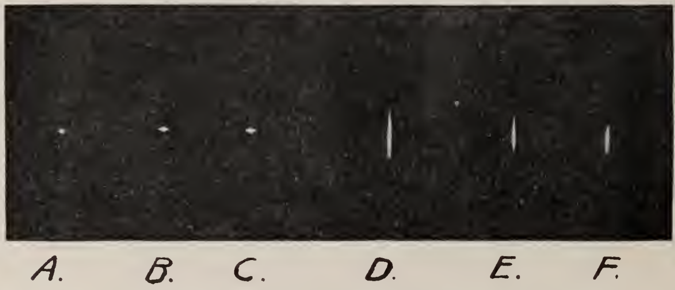

FIG. 15.—(*a*) *Without glass;* (*b, c*) *viewed flatwise through rolled window plate* (*same as Fig. 10*); (*d, e, f*) *edgewise through same plate*

good so far as the unaided eye could distinguish—far better than those obtained with many binoculars in which the amount of striæ present was negligible.

A lot of prisms and lenses, rejected after polishing, were turned over to this Bureau by the optical shop annex of the Naval Gun Factory at Rochester. These prisms were discarded on account of striæ, bubbles, and scratches, the polish and workmanship in all cases being above criticism. All of the prisms shown in Fig. 3 were taken from this lot of rejects, the prints to the left being shadowgraphs of the striæ in the prisms. Dr. Zwillinger, of the optical shop annex, loaned the authors a testing frame into which the different parts of a binocular could be fitted at pleasure. By inserting single, discarded parts in an otherwise first-class optical

FIG. 16.—*Striæ in large photographic lens*

train the authors demonstrated visually to their own satifaction that only relatively heavy striæ were an appreciable drawback to the performance of the prisms and lenses tested. In fact, of the lot of six prisms shown only No. 1 was really very bad in its performance, and the striæ in the lens of Fig. 8 seemed to exert no noticeable effect upon the definition.

To obtain a record of the amount of light scattered by the striæ in these prisms, each one was inserted in a train otherwise good, and then this was used as a part of an optical-projection system to project a magnified image of an artificial star—or, perhaps, in this case it would be more correct to say an artificial planet, for the pinhole was about 0.8 mm in diameter—on a photographic plate.

Because of the fact that the binoculars are chromatically corrected for visual impression rather than for photographic record,

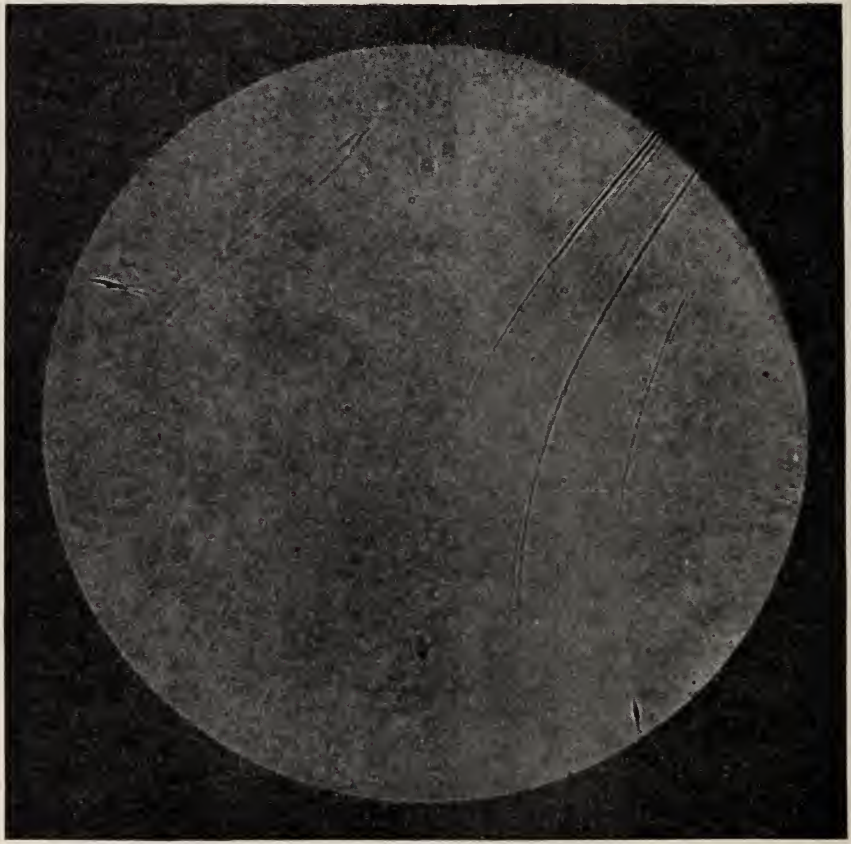

Fig. 17.—*Striæ in a 5-inch telescope lens*

orthochromatic plates were used, and a Wratten and Wainwright K_2 screen, which absorbs strongly in the violet, was placed just before the pinhole. In order to give some idea of the relative intensity of the scattered light to that of the central image, a series of exposures, shown in the sequence left to right (Fig. 3), was taken, starting with one-half second and doubling the time for each successive one until the eighth exposure was for 64 seconds.

In the case of prisms 3 and 4, the one-half-second exposure was unintentionally omitted.

It is apparent from these reproductions that the damage done to the image by the prisms 4, 5, and 6, is hardly noticeable. In the case of prisms 2 and 3 the scattered light is pronounced, but it is apparent from the figure that the central spot is relatively much more intense than the streamers of scattered light. This is, without doubt, the explanation of the fact that the observed definition in these cases is very fair. Only in the case of prism 1 is the scattered light not of relatively small intensity, and in the case of this prism the definition was noticeably poor on a visual test.

II. INDEX OF REFRACTION

As already stated, the scattering of light by striæ is due to the difference between the refraction of the striæ and that of the surrounding glass.

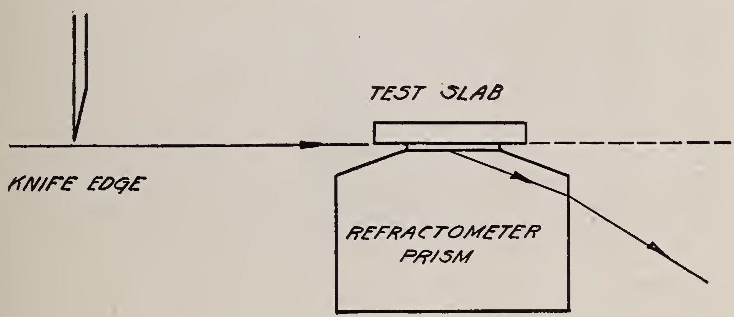

FIG. 18.—*The Pulfrich refractometer*

The knife-edge serves to cut off the oblique rays, and thus gives "lines" in the observing telescope

In testing the index of refraction of optical glass produced by this Bureau at its Pittsburgh branch it was noticed that some of the test prisms for the spectrometer and some of the test slabs for the Pulfrich refractometer gave multiple lines in the field, and also that these samples contained heavy striæ. The spectrometer, dealing with transmitted light, offers no simple interpretation of the difference in deviation; but in the case of the Pulfrich refractometer, where the magnitudes depend upon the critical angle of total reflection, the conditions are simpler. With the latter instrument the position of the edge of the illuminated field indicates the refractive index of the lower surface of the test slab where it is in contact with the monobromonaphthaline lying between it and the high-index prism of the refractometer (Fig. 18).

By using the knife-edge attachment with which the instrument is provided the field may be reduced, in the case of a monochromatic source of light, to a single, narrow band. This is because the knife edge cuts off oblique rays, allowing only those which are practically parallel to its lower face to enter the test slab. By adjusting the knife edge this band may be made to appear as a spectral line. If now, as seen in Fig. 19, there is a stria in the lower face of the test slab, a second spectral line appears on the one side or the other of the main line, depending on whether the stria has a higher or a lower refractive index than the rest of the glass.[2]

Fig. 19.—*Striæ in Pulfrich test slab*

The index of the stria in this sample differs from that of the surrounding glass by 0.0002

In measuring the index of the stria by this method it is necessary to distinguish between the doubling of the line by the stria and the frequently observed doubling by accidental causes. Certain tests enable the following distinctions to be drawn:

1. If the doubling be due to a stria, any adjustment of the instrument which eliminates the second line causes the first also to vanish, but not if the second line arises from an accidental cause.

2. A small shift of the test slab on the table will often eliminate lines, while a relatively large shift is usually necessary to carry a stria out of the field.

3. Finally, if the doubling arises from a stria, the effect is observed to appear for certain definite positions of the slab as it is shifted back and forth on its table, which is not the case with accidental doubling.

By a combination of these criteria and a little experience in applying them there need be no doubt left in the mind of the

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[2] In this photograph the identifying mark ($X-\alpha$) shows through from the back of the slab.

observer as to whether in a given case the observed phenomenon is due to a stria or not.

In dealing with a nest of striæ it sometimes happens that several lines appear in place of the simple doubling. This, of course, is to be ascribed to the presence of striæ possessing different refractive indices. In the present work the measurements were confined to cases where simple doubling of the lines occurred.

Samples of glass containing specially heavy striæ were picked out at the factory, and slabs were prepared from these in our optical shop, in which the striæ cut across the lower face of the slab nearly parallel to its long edge. The striæ were consequently nearly parallel to the plane of the figure in Fig. 18. The spectral lines due to the striæ were then distinct, and their index could be determined with nearly the same accuracy as with a piece of clear glass. The results so obtained for the *C*, *D*, and *F* lines are shown in Table 1 for seven different samples of glass. The *D* line was obtained from sodium in a Bunsen flame, the *C* and *F* lines from a hydrogen spectrum tube. For each sample the refractive indices of the glass are given first, with those of the stria following. The difference between the refractive index for the glass and for the stria is given in the third line, indicated as positive when the stria has the larger refractive index; negative when lower. These differences are in all cases smaller than four in the *fourth* decimal place. It will be observed that out of the seven samples, the striæ in four of them have a lower refractive index than the surrounding glass, while in the other three the index is higher. From these results we may conclude that the striæ are just as likely to have a higher index than the glass as a lower. Some measurements made at this Bureau on a very pronounced sheet stria at the same time, but published earlier[3], showed that the refractive index of the stria in that case was smaller than that of the surrounding glass by about four in the *third* decimal place.

It is to be noted that six of the seven samples tested show that the striæ change the refractive index of the red (*C* line) more than the blue (*F* line). Such a conclusion is unexpected and should not be accepted without a careful consideration of the possible errors of measurement. Since the observed doubling of the lines never entirely separates them and since the settings are made on corresponding edges of the lines, the observer locates one edge of the pair against a dark background and the other against a light

[3] A. A. Michelson, B. S. Scientific Paper, No. 333, pp. 41–45; 1918.

one. This of course obtains for both colors; but, inasmuch as the *C* line is distinctly brighter than the *F* line, contrast conditions might make the apparent shift greater in the red than in the blue.

TABLE 1

SAMPLE X.—BOROSILICATE CROWN (SPECIALLY MARKED STRIÆ, SEE FIG. 8)

	D	C	F
Glass	1. 51616	1. 51370	1. 52198
Stria	1. 51637	1. 51393	1. 52216
Difference	+21	+23	+18

NO. 169.—LIGHT BARIUM FLINT

	D	C	F
Glass	1. 54792	1. 54485	1. 55525
Stria	1. 55810	1. 54504	1. 55541
Difference	+18	+19	+16

NO. 33.—LIGHT BARIUM CROWN

	D	C	F
Glass	1. 57565	1. 57272	1. 58278
Stria	1. 57547	1. 57250	1. 58264
Difference	−18	−22	−14

NO. 255.—MEDIUM FLINT

	D	C	F
Glass	1. 62135	1. 61666	1. 63339
Stria	1. 62113	1. 61647	1. 63316
Difference	−22	−19	−23

NO. A211.—MEDIUM FLINT

	D	C	F
Glass	1. 62401	1. 61921	1. 63609
Stria	1. 62374	1. 61895	1. 63584
Difference	−27	−26	−25

NO. 332.—LIGHT BARIUM CROWN

	D	C	F
Glass	1. 57153	1. 56868	1. 57849
Stria	1. 57129	1. 56846	1. 57828
Difference	−24	−22	−21

NO. 339.—LIGHT BARIUM CROWN

	D	C	F
Glass	1. 57023	1. 56731	1. 57745
Stria	1. 57062	1. 56768	1. 57772
Difference	+39	+37	+27

III. SUMMARY AND CONCLUSIONS

Different methods, varying greatly in sensitiveness, are described for revealing the presence of striæ, and corresponding photographic illustrations are given. In addition to photographs of the striæ in a number of samples, there are given also photographs of an artificial star viewed through the same samples.

The refractive indices of the striæ, along with those of the surrounding glass, are measured for a number of different samples by the total-reflection method. These show the srtiæ to have a refractive index in some cases larger, in others smaller, than the surrounding glass by as much as three or four in the fourth decimal place, but usually about two.

The effects of the striæ may be placed in two classes, as follows:

1. With striæ somewhat out of focus a shadow may be thrown across the field of view. This is likely to give trouble in only cases where they are in focus, or nearly in focus, as with the collector lens in an eyepiece or in the nearer prisms of binoculars. However, the effect in this latter case has not been observed in the course of our work.

2. The image of a bright point will have streamers of scattered light, caused by the striæ. These will, in general, do little damage in visual work, unless the striæ cover a comparatively large part of the aperture of the beam of light. In astronomical and certain classes of microscopic work this scattered light would probably be injurious.

WASHINGTON, November 10, 1919.