PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

On Artificial Temporary Colour-Blindness, with an Examination of the Colour Sensations of 109 Persons

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PHILOSOPHICAL TRANSACTIONS.

I. *On Artificial Temporary Colour-Blindness, with an Examination of the Colour Sensations of* 109 *Persons.*

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[PLATES 1, 2.]

CONTENTS.

GENERAL PHENOMENA.

BY artificial colour-blindness I mean the extreme forms of that altered condition of the eye, described two centuries ago by DE LA HIRE, and probably familiar to most people, which can be produced by looking at the sky for some minutes through a piece of coloured glass.

It is possible, apparently without serious risk of injuring the eyesight, by exposing the eye to the action of a more intense monochromatic light, to induce a condition of complete blindness to one or more of the primary colours, lasting some three or four minutes, and enabling the observer to experience in his own person the sensations of the colour-blind.

In a paper read before the meeting of the Physiological Society at Oxford in 1895, I referred briefly to some of my experiments in this direction, and, having recently taken measurements of the colour sensations of seventy persons by a modification of this plan, I propose in the present paper to give an account of the results.

Between the almost imperceptible lessening of any one of the primary colour sensations and its complete temporary abolition there are many stages, but no essential difference of effect, and the same general phenomena are observable alike with strong sunlight and with the faintest light the eye is capable of perceiving.

The points of difference relate rather to a branch of the subject which I propose to discuss in a separate paper on the "Dunkeladaptirtes Auge."

General Phenomena of Artificial Colour-Blindness.

The method by which I first proved the possibility of producing temporary colour-blindness is so very simple, that probably only the fear of injuring the eyesight by such a procedure has deterred observers from the free use of it. It consists in exposing the eye to bright sunlight in the focus of a burning glass behind a transparent screen of the proper colour, and keeping it there until all sensation of that particular colour is lost. The time necessary to produce this condition varies with the season of the year, the altitude of the sun, the health of the observer, and the colour of the transmitted light, but it is easy to recognise, by the change in the character of the sensation, when the exposure is sufficient. On removing the eye from the lens the glare of the positive after-effect is at first so strong that everything seems hidden behind a luminous fog, but after a few seconds this diminishes until it is only noticeable on feebly illuminated objects. But for some time all direct sensation of the colour used for fatiguing the eye is completely lost, whereas its sensitiveness to all other colours is undiminished. The observer is, in fact, colour-blind. From this condition he recovers, in the case of the red light, in about ten minutes. The effect of the green light lasts longer, and that of blue light longer still, while the recovery from violet-blindness may require a couple of hours.

Although for purposes of exact observation it is necessary to use a train of prisms, the principal phenomena may so easily be demonstrated with coloured screens that it may be worth while to describe briefly those I have found best adapted for the purpose.

For producing red-blindness ordinary ruby glass is not sufficient. If deep, it transmits too little light, and if pale, it allows green rays to pass in sufficient quantity to vitiate the results. A gelatine film stained with magenta or *fleur de Paris*, used in conjunction with a medium ruby glass, gives a very pure red.

A suitable green may be got with three thicknesses of green glass (coloured with cupric oxide), and a tank filled with solution of ammonio-sulphate of copper serves for the violet. Hitherto I have not succeeded in obtaining a perfectly satisfactory blue, save with prisms.

The method of proceeding is as follows: Placing an ordinary pocket lens of about

2 inches focus against the coloured medium I hold it up to the sun at such a distance from my eye that the light appears to fill the entire lens. Thus a large area of the retina is affected, and this is essential.

With the combination of ruby glass and magenta referred to it takes from a few seconds to two or three minutes to produce complete red-blindness. My earlier experiments were conducted out of doors, and I shall not easily forget the weird appearance of the flower garden as I first saw it under these conditions. For some time after the eye is taken from the light scarlet geraniums appear black, calceolarias and sunflowers various shades of green, brighter than green leaves, and marigolds green shaded with black in the parts that are orange to the normal eye. Purple flowers, such as candytuft and clematis, look violet, and pink roses bright sky-blue.

With HOLMGREN'S wools exactly the same mistakes are made as by the red-blind, several of whom have also described the blue of the spectrum to me as "rose colour." The effect passes off very rapidly, and in ten minutes is scarcely noticeable.

With the violet solutions of ammonio-sulphate of copper a condition is produced which in some respects resembles that of the violet-blind. Violet wools look black, and purple flowers crimson. Some kinds of warm blue assume a decided green tint. Greys and drabs become fawns and browns, and the green foliage appears of a rich warm colour, beside which its hue to the unaltered eye is glaucous.

In one respect, however, there is a noticeable difference between the appearance of the flower garden to an eye in this condition and to an eye simply incapable of being affected by violet. This difference is most readily seen in the altered hue of red flowers, such as scarlet geraniums, which appear crimson. The colour by which the eye has been dazzled, and to which it is now blind, tints all those objects which naturally reflect none of it. Farther reference will be made to this phenomenon.

To produce temporary green-blindness three thicknesses of green glass suffice. The colour-scheme of the landscape for the first few moments after removing the eye from the light is exactly that of a picture painted with vermilion, ultramarine, and flake-white, variously blended. The foliage is either reddish-grey or bluish-grey. Blue flowers are blue, but a trifle dirty. Red flowers are red, but the tint is not quite pure. The eye seems incapable of perceiving green, and yet every other colour is tinted with the green by which it has been dazzled.

As the effect passes off, it is as if orange-chrome, Naples yellow, and cobalt, and finally chrome-yellow and Prussian blue, were in succession added to the palette.

The converse of green-blindness may be easily produced by exposing the eye as before to sunlight, using a purple screen composed of gelatine films stained with magenta and aniline violet. By taking several thicknesses of each, the absorption of the green and blue may be rendered complete. The combination of red and violet rays produces in my own case a distinctly painful sensation when bright sunlight is used, which is not felt with either red or violet separately. The result is to render the vision for a short time almost absolutely monochromatic, everything appearing some shade of emerald green. After a little while the red begins to recover, and the observer is then in a condition of artificial violet-blindness, which passes off almost completely in from fifteen minutes to an hour, according to his state of health.

During the condition of purple-blindness all red, purple, or blue flowers look nearly black, but the grass appears of a brilliant rich green, beside which its colour to the normal eye is dirty by comparison.

The following experiment, perhaps the most remarkable of any, is of considerable importance as regards the theory of colour sensation. I made my right eye purple-blind, and my left eye green-blind simultaneously. The effect upon the landscape was weird in the extreme. Everything—trees, houses, flower garden—appeared in its natural colours, but with a most curiously exaggerated perspective, somewhat resembling that of a bad stereoscope. The scarlet flowers of the geraniums seemed to have nothing to do with the green leaves, but to be suspended in the air above them, while the white and yellow flowers appeared to form double images with complementary colours, which it was very difficult to bring together.

On the Appearance of the Spectrum during the Condition of Temporary Colour-Blindness.

In order to investigate systematically the phenomena of temporary colour-blindness I adopted the following plan :—A horizontal beam of sunlight from a heliostat was passed through a series of prisms fixed at a convenient height above the ground. About 20 feet away I placed a convex lens of 3 inches focus in the path of the refracted rays, adjusting its position until, on examining the light collected by it with a hand spectroscope, it was found to include only that portion of the spectrum which I desired to use.

I then exposed my eye for a few seconds to the extremely bright light in the focus of the lens, and immediately afterwards looked through a single-prism spectroscope illuminated by the light of the sky, comparing the results with those given by the other eye, which had not been exposed to the light.

After a sufficient interval I repeated the process, fatiguing the eye with light of a different wave-length. In this way I went over the entire spectrum, shifting the lens through about half the range of wave-lengths collected by it for each fresh experiment, and always taking care to allow the effects of one exposure to pass off completely before commencing another.

By these preliminary explorations many times repeated, I ascertained that the following parts of the spectrum, namely: the red from A to B; the green from the neighbourhood of E; the blue about half-way between F and G; and the violet at and beyond H, produce well-defined and characteristic results, whereas the intermediate portions of the spectrum produce results that are intermediate in character.

That is to say, if certain changes in the appearance of the spectrum are brought about by fatiguing the eye with red light, and certain other changes ensue after its exposure to green light, then those portions of the spectrum which lie between the red and the green—for instance the orange or the yellow—instead of producing a corresponding set of changes in the orange or the yellow affect the whole of the red and the whole of the green, both where they appear separately and where they are mixed with other colours, the total change being identically equal to the sum of the changes due to excitation by red light and green light separately.

I found three regions of the spectrum which induce changes of colour sensation of this complex or intermediate character, namely, the whole range of orange and yellow tints, the blue-greens, and the various shades of indigo.

I found four regions of the spectrum which cause more simple changes, namely, pure red, pure green, pure blue, and pure violet.* The effects produced by each of these four colours differ in degree but not in kind. They are as follows:—

(1.) In each case all direct sensation of the colour used for fatiguing the eye is practically lost, not merely from the corresponding part of the spectrum, but also from those regions in which it overlaps the other colours.

(2.) The colour used for fatiguing the eye produces a positive after-effect of the same colour like a luminous fog, by which the hue of all the other colours is modified if they are relatively weak, but which is unnoticed if they are bright.

(3.) The temporary abolition of any one colour sensation is without effect on the intensity of the remaining colour sensations, neither increasing nor diminishing them unless they also have been to some extent implicated in the light used for producing colour-blindness.

(4.) Any two or any three of these four primary colour sensations can be simultaneously or successively exhausted, and the condition of colour-blindness maintained for as long as may be convenient.

(5.) As regards duration and degree, the positive after-effect of red is very transient; that of green lasts longer; that of blue is still more powerful and persistent; and that of violet is strongest, and lasts a long while.

The subsidence of the positive after-effect is in each case accompanied by the gradual return of the colour sensation, the red recovering in about ten minutes, while the violet sometimes takes two hours. But the positive effect becomes unnoticeable long before the colour sensation is restored to its full strength.

(6.) In the bright light used for dazzling the eye the observer is distinctly conscious of the progress of the change. In the case of green and blue these colours die out of the spectrum, but with red and violet the colour remains, though of greatly diminished intensity, and the observer only realises his colour-blindness on attempting to examine a less brilliantly illuminated spectrum.

* In reality, no part of the spectrum produces a pure sensation of colour except the two ends of it. The word "pure" is here used to describe colours not obviously mixed.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

(1.) With regard to the first point it is important to note that in the typical cases it is the sensation of a particular colour that is weakened, rather than the sensitiveness of the eye to certain parts of the spectrum.

Thus in red-blindness the spectrum is shortened at the red end because that colour no longer affects the eye, but the green, which to normal vision is masked by the red over the part occupied by yellow and orange, now appears with full intensity at D, and reaches more faintly almost as far as C.

On the other hand in green-blindness there is no part of the spectrum absolutely devoid of light. The green disappears, but its place is occupied by the red and blue, which not only meet, but overlap, as indeed they are shown to do in the curves of colour sensation arrived at by the method of mixtures. I have, however, occasionally seen for a few moments a distinct absorption-band in the green during green-blindness, and in the blue during blue-blindness.

But no doubt in both cases it is not merely the green or the blue that has been fatigued, but in a less degree also the neighbouring colours, since there is no portion of the spectrum, except the two ends of it, which excites one colour sensation without also exciting some traces of a second or even a third.

(2.) A few words of explanation may be necessary with regard to the second point. So far as it relates to mixed colours the phenomenon has been familiarly known ever since the time of KIRCHER. It is, however, generally complicated with conditions which do not obtain in my experiments. Just as negative after-images are seen on a bright background and positive after-images on a dark one, so each colour sensation that has been fatigued disappears from the part of the spectrum to which it belongs, but superposes itself like a positive after-image upon every other colour. Under ordinary circumstances a positive after-image is the sum total of the positive after-effects of more or less mixed light-vibrations. Each of the several colour sensations which have been excited has its own rate of development and of subsidence. Each, moreover, spreads laterally at the borders of an image to a different extent. I have some fear, therefore, lest without an explanation, or the use of some different term, what I have to say about positive after-effects should seem contradicted by the experimental results obtained by other observers, of which it is in truth the explanation.

A strong light not only fatigues the eye, but dazzles it; that is to say, the sensation of light persists after the source of light has been withdrawn. If the bright object has a definite outline, this phenomenon may be described as the positive after-image, or if no outline is conspicuous, as the positive after-effect. But for my present purpose a name is needed for the elementary component sensations of this positive after-effect. I have been accustomed in my own note books to use the term "dazzle tint" in this sense. It implies no theory, being purely descriptive, and its use in this paper may prevent my descriptions from being misunderstood.

I define the term as follows:—The positive after-effect or after-image of a luminous object is made up of as many dazzle-tints as there were colour sensations excited by it. The dazzle-tint of red is red, that of green is green, that of blue is blue, and that of violet is violet.

Each dazzle-tint has its own rate of development and of subsidence, and each one is independent of the rest. The positive after-effect of a spectral colour is at first of the same colour as the light that produced it, but of very much smaller intensity. It mingles with the colour of every object looked at, but is only detected when the real luminosity of the object is not many times greater than the subjective luminosity of the dazzle-tints. If the object is very feebly illuminated, it may be completely hidden by the positive after-effect as by a luminous fog. But the dazzle-tints die out one by one, red first, then green, then blue, and last of all violet. Consequently the colour of the positive after-effect undergoes a series of changes depending on the proportions and nature of its constituent dazzle-tints. KIRCHER pointed out that if after looking at the sun a person look at any dark object, the image in his eye will be first white, then yellow, then red, then green, and finally blue, and it is a matter of common experience that such after-images undergo a cycle of changes which may be repeated several times.

No such effect is appreciable in the experiments with spectral colours described in this paper. The cyclic changes are, I believe, partly due to the excitation of a limited portion of the retina, which seems to induce a subjective conflict between the positive and negative after-effects. But in my experiments the positive and negative after-effects are completely separated. If the eye has been fatigued, *e.g.*, by mixed violet and blue light, no positive after-effect is visible on the blue and violet parts of the spectrum. These colours are simply blotted out. But the green and the red act as a black background so far as blue and violet are concerned, and the positive after-effect shows up strongly against them. It consists of two dazzle-tints, one of which, namely blue, dies out long before the other, and, consequently, the apparent hue of the red gradually changes from a crimson to a pure red-purple, and the green from a steel-blue to a peculiar whitish tinge. But there is no noticeable repetition of this series under ordinary circumstances.

Similarly the positive after-effect of light from between D and C is at first red. But it comprises two dazzle-tints red and green, of which red soon vanishes, leaving green.

The after-effects of light filtered through coloured media, or reflected from pigments, are for the most part very complex and for that reason misleading.

I have attempted to make coloured diagrams of some of the typical cases, but find it impossible to match the tints in water colours. My diagrams (see Plates 1 and 2) which accompany this paper may, however, serve, though imperfectly, to indicate the main points.

Plate 1, fig. 1. Is a normal spectrum for comparison.

Fig. 2. After exposure to sunlight from between A and B.

All sensation of red is lost, the spectrum beginning with pure green a little beyond C. The D-lines appear bright green. The blue-green, blue, indigo, and violet are unaltered in position or intensity. Even while so far blinded by the intense light as to be unable to read large print, I can see the violet of the spectrum well beyond K. With a narrow slit the green appears of a more leaf-green hue, the blue becomes more ultramarine and the violet slightly purple in tone. This effect passes off in about 30 seconds, and the red sensation recovers in about 10 minutes.

Passing on to the more refrangible parts of the spectrum we come to a region giving effects of greater complexity. If the light used extends much beyond B, although the red sensation is exhausted more readily than before, the green also begins to appear less bright, not merely on the side next the red, but throughout its whole extent.

With light from C the effect upon the green is very marked, and it is evident that in the fatigue produced by light from D the red and the green colour sensations are about equally involved. After a very brief exposure to light of this wave-length the spectrum, although visible from A to K, is seen to be uniformly dulled from A to b, the red appearing brick red, and the green yellowish and dingy. A more protracted exposure to the light abolishes the red and green sensations altogether.

This effect is very strikingly shown by fatiguing a portion only of the retina.

Fig. 3. After sunlight from D, using screens so as only to fatigue a horizontal band across the middle of the retina.

The whole of the *red and green* are missing from the part of the retina subjected to the light. The spectrum begins with pure blue a little beyond b, and extends to the end of the violet beyond K. The difference in hue between blue and violet is as well marked as in the normal spectrum. The orange light with which the eye was blinded tints both the blue and the violet when a narrow slit is used, making the blue paler but more luminous, and the violet more luminous and slightly inclining to purple. As the red dazzle-tint dies out the positive after-effect becomes green, and the red end of the spectrum begins to reappear. But the direct sensation of green does not return until the green dazzle-tint has completely subsided.

Beyond D the effect on the red diminishes and that on the green increases till we come to E, which seems to correspond very nearly with the point of maximum sensitiveness to green. The results are shown in figs. 4 and 5.

Fig. 4. After sunlight from E over the whole retina.

The condition is one of green-blindness. It is, in my own case, more easily produced than that of red-blindness, but the appearances are apt to be misleading owing to the very powerful positive after-effect of green. If the slit is narrow the spectrum seems to consist of two colours only, namely, orange-chrome and ultramarine, passing into each other through a neutral tint very difficult to describe. This condition is represented in fig. 5.

But on opening the slit the orange changes to a brilliant scarlet, reaching almost up to the blue, with only a narrow band of neutral tint between, and the violet is also plainly differentiated from the blue as in the normal spectrum. This state is represented in fig. 4. By simply opening or closing the slit the change can be effected at any time during the duration of green-blindness, showing that the orange hue of the red is due to the admixture with it of a subjective green (the positive after-effect), the intensity of which is a function of the time, and not of the width of the slit at the moment, and which is therefore unnoticed when the brightness of the spectrum is sufficiently increased. I was struck with the remarkable resemblance of the spectrum during green-blindness, when the slit is nearly closed, to the illustration of "Colour-Blindness Induced by Disease," in the Report of the Committee on Colour-Vision.*

Sunlight from *b* abolishes the green, but perceptibly dulls the blue also, and as we pass towards F the blue becomes more and more implicated. A wider dispersion is required for experiments on this part of the spectrum if the object is to fatigue the blue and violet separately. Blindness to both simultaneously is easily produced by light from the neighbourhood of G.

The positive after-effects are very powerful and striking. As long as there is any excitation of green by the light used, the red of the spectrum is more or less orange, but in proportion as the blue is implicated, the orange tone gives place to a peculiar tinge of scarlet. When we get clear of the green the positive after-effect of the blue makes the red look crimson, and the green slightly paler and of a bluish hue. But after sunlight from anywhere beyond G the red end of the spectrum looks bright purple, while the green assumes that peculiar colour which results from blending spectral green with spectral violet, and which is by many persons called white. To myself it is quite unlike white. The blue and the violet are either much diminished in intensity or else completely absent.

Figs. 6 and 7 illustrate this condition. Sunlight from between G and H was used for fig. 6. The slit was rather narrow, and the positive after-effect had nearly passed off. The spectrum ends a little beyond F, both blue and violet being abolished.

In fig. 7 the exciting light was taken from the region near G. By some chance the green was slightly fatigued as well, and the spectrum barely reached F. The red is of a purplish hue, and the green that remains is strongly affected by the positive after-effect.

I have already stated that it is possible to exhaust any two or any three colour sensations either simultaneously or in succession. An extremely interesting case is afforded by the next example.

Plate 2, fig. 8. After sunlight from G followed by sunlight from E.

Sunlight from G produces colour-blindness to blue and violet, lasting long enough to give ample time for the subsequent exhaustion of the green colour sensation by light from E. The same effect might be produced in one operation by taking in all

* 'Proceedings of the Royal Society,' 1892, vol. 51.

the light from *b* to the end of the spectrum, but this I found to be somewhat painful and quite unnecessary. It is, moreover, easier to judge when the exhaustion is complete if the colours are taken separately.

The result is that only the red sensation is left. It extends from A to midway between *b* and F. Owing to the extremely powerful positive after-effect of the three colours to which the eye is blinded, the red is pale in hue, but unmistakably red up to its limits and not in the least orange. It is interesting to consider what, in the light of the other observations, the colour of this red ought to be. The positive after-effect contains three dazzle-tints, green, blue, and violet. All of these must be active in the region from A to C, because the light from that part of the spectrum excites none of these colours. The green and the violet will balance each other as regards their effect upon the hue, and the blue will accordingly impart a tinge of crimson to the red. Farther on, in the region normally occupied by green, the green dazzle-tint will be inoperative; for those parts of the spectrum in which a *negative after-effect* (fatigue effect) *has been produced, seem to lose the power of bringing out the corresponding positive after-effect* (dazzle-tint) *of that colour.* Accordingly, the feeble traces of red which extend beyond E and *b* will excite *only the blue and violet dazzle-tints, and not the green*, and will, therefore, appear distinctly purple. As a matter of fact, with a very narrow slit the spectrum seems for the first few moments to end between *b* and F in a purplish slate colour. But on opening the slit the red asserts itself.

Fig. 9, which serves by contrast to bring out the colours of fig. 8, represents the appearance of the spectrum towards the end of recovery from violet-blindness. The positive after-effect has nearly passed off and the colours have their normal hue, but the violet is still invisible.

Fig. 10 shows the appearance of the spectrum during purple-blindness produced by exposure to sunlight, filtered through magenta and aniline violet. Only the green sensation is left. It extends brightly from D to F, but is visible nearly as far as C on the red side and G on the violet side. It is of the same colour throughout, somewhat like emerald green, but with less inclination to blue. With a narrow slit it looks almost white owing to admixture with the purple positive-after-effect. The red recovers first, then the blue, and finally the violet.

Observations with the Marlborough Spectroscope.

For the minute examination of the changes in the spectrum during the various kinds of temporary colour-blindness, a spectroscope was required of greater power than my own, and for some years I discontinued my experiments.

In 1892, the valuable collection of instruments belonging to the late Duke of Marlborough, including, besides chemical and electrical apparatus, three large spectroscopes, with a number of accessory appliances, was presented to the University of Oxford by the DOWAGER DUCHESS OF MARLBOROUGH.

One of these spectroscopes happened to be peculiarly well adapted for the purposes of this research, and I am indebted to Mr. W. W. FISHER, Aldrichian Demonstrator of Chemistry, in whose custody it was placed, for permission to make free use of it. By the kindness of Professor GOTCH a room was assigned to me in the Physiological Laboratory, where I could have the use of the arc-lamp when sunlight was not available.

The instrument in question is a large direct-vision spectroscope by HILGER. The light from the slit after passing through the collimator is refracted by the first prism on to a second, in which, after a second refraction, it undergoes two internal reflections, and is refracted on emerging into a third prism, through which it passes to the observing telescope. The first and third prisms are coupled together so that they can be rotated in opposite directions by means of a rack and pinion. There are three eye-pieces, the two highest having cross-wires, and the lowest a pointer, and the position of the lines is read off on a graduated arc attached to the axis of rotation of the first prism.

The instrument was specially convenient for this research owing to the rapidity with which the slit could be opened or closed, or the spectrum traversed from one end to the other, all the adjustments being brought within reach of the observer by connecting rods. The angular separation of the D-lines is about 13′, but the dispersion increases rapidly in the violet, and beyond K the graduation is not reliable. For experiments requiring a greater dispersion I used a Huyghenian eye-piece of short focus belonging to one of my own instruments.

With this spectroscope a curious phenomenon, visible only in spectra of considerable length, is easily seen. As long as the observer is engaged only in measuring the position of the Fraunhofer lines the tints appear perfectly steady, but if he concentrates his attention on their colour he becomes conscious after a while of a species of flickering in certain parts of the spectrum.* Thus, in the region of the D-lines, waves of red and green appear to pass to-and-fro across the field of view, rendering it impossible to fix the neutral point between the two colours. Most people notice this without being told what to expect, if asked to find the pure yellow. A similar flickering is observed in the blue-green, both by the red-blind and by those who have normal vision. The region between blue and violet also shows the same phenomenon, but to most people it is less rapid and well marked here than in the yellow. I have, however, come across several who found the flickering very strong between blue and violet.

It will be observed that the three regions in which "flickering" occurs are identical with the three regions of the spectrum, which, in the experiments on temporary colour-blindness, produce complex effects. And it will be shown in the following pages that during temporary blindness to green this flickering is visible at the

* See 'Proceedings of the Physiological Society,' June, 1897.

junction of red and blue, and farther that during temporary blue-blindness it appears as strongly at the junction of green with violet.

With the Marlborough Spectroscope I made four series of experiments, viz.:—

I. With a wide slit and direct sunlight I fatigued my eye with light of known wave-length and observed the result in a single-prism spectroscope standing close by on the table. In this way I repeated and confirmed my old observations.

II. Using a short slit so as to produce a narrow horizontal band of practically monochromatic light, I fatigued only a portion of the retina, taking care to fix my eye on the junction of the cross-wires. On looking subsequently through the single prism spectroscope, which has a very large field of view, a sort of subjective absorption-spectrum due to the fatigued portion of the retina is seen, and the various changes of hue consequent on the addition to the remaining colours, of the positive after-effect or dazzle-tints, can be easily studied and compared with those of the unaltered parts of the retina.

In my older experiments I effected this result by using a binocular spectroscope with complementary screens in the eye-pieces, so that the right eye saw only the middle part of the field and the left eye its upper and lower portions. Either method will serve, though each has some advantages.

III. With a high power, and the full length of the slit so that the field of view is completely filled with practically monochromatic light, I open the slit to its full width, and, having induced the condition of temporary colour-blindness, suddenly close the slit till the Fraunhofer lines are visible, and traversing the spectrum quickly note the exact position of the various changes of hue.

IV. Keeping the slit constantly of the same width, with a moderate degree of illumination such as would be chosen for comfortable observation, I direct the observer to look steadily for a definite period (30 seconds) at light of a known wave-length, and then at the word of command, quickly to traverse the spectrum until the beginning of the first change of hue reaches the middle of the field.

By this method I have examined and compared the colour sensations of seventy persons.

The results will be found in the concluding section of this paper.

III.

I now proceed to describe my investigation by the third method of the details of green-, blue-, and violet-blindness.

(Details of green-blindness, see fig. 11.)

With direct sunlight and the highest eye-piece I brought the D-lines to the extreme left and the *b*-lines to the extreme right of the field. This places the centre of the field in the part of the spectrum producing in my own case the greatest intensity of the green sensation.

I then opened the slit till the light was as intense as I could bear. After about 30 seconds the green tint gave place to a warm reddish-yellow on the left and a blue on the right. On closing the slit until the lines were sharply defined, the green was seen to have entirely vanished, all to the left being scarlet and all to the right indigo, the scarlet fading to a pale red, and the indigo to a pale blue, with a neutral colour, difficult to describe, where the two met (fig. 11, *a*). The junction was at 675 of the scale (about λ 5241), but it flickered rapidly, with a strong tendency for the red to encroach on the blue.

Above and below the spectral band was a strong green dazzle-tint which was not a mere contrast effect, for if the slit was closed so as to make the spectrum fainter this subjective green mingled with the hues of the spectrum and made the blue cold, and turned the red-yellow right up to its limit.

But, on again opening the slit a little, the red became scarlet, and the blue indigo. On turning to the more refrangible end of the spectrum I found the beginning of the violet well marked at 861 scale (about λ 4470), where I usually see it. I then went back again to the region of the green sensation, and after a second exposure of a few seconds to the bright light, to neutralise any traces of its recovery, I turned to the red between A and B, and fatigued the eye with that.

Closing the slit and quickly racking back again, I found blue reaching to 656 (about λ 5370) (fig. 11, *b*).

The dazzle-tint was now rose-coloured for about 10 seconds, after which it quickly passed through orange to green. At the same time the blue receded and the red encroached upon it until the neutral point was again at 675 scale (λ 5241).

Judging from this that the red sensation had now practically recovered, I once more opened the slit for a couple of seconds to keep back the green, closed it, and racked quickly over to the blue just beyond F.

Here I dazzled the eye for about 5 seconds with strong blue light, then closed the slit till the lines were well defined, and racked back again, meeting the red now at 715 scale (about λ 5040) (fig. 11, *c*). Keeping my eye fixed on the junction between the two colours, I saw the red gradually retreat and the blue encroach upon it until the neutral point was once more at 675 scale (λ 5241).

But the blue was so much longer in recovering than the red, that by this time the green had begun to be perceptible. Exposure to light from the neighbourhood of H has no effect on the position of the junction of red with blue.

During all this time (nearly half an hour) the right eye saw the limits of the green in their usual positions and its intensity did not appear to be affected, nor indeed was I conscious of anything abnormal in the colour perceptions of the right eye. I therefore decided to use the right eye for the corresponding experiment on the blue colour sensation.

I placed the cross-wires at λ 4700 and opened the slit wide for about 30 seconds. On closing it again, till the Fraunhofer lines were well defined, I found the green meeting the violet with scarcely any really neutral* space between at 800 scale (about λ 4630). The boundary between them was not fixed, but seemed to sway to-and-fro according as I looked to one side of the field or the other.

I was not able to complete the experiment by fatiguing successively the green and violet also, as I had done with the red and blue while investigating green-blindness, owing to clouds covering the sun, but a few days later I had an opportunity of doing so. It was an unusually clear day, and the violet end of the spectrum was very bright. Hitherto my attempts to blind myself to violet without fatiguing the blue had not been entirely successful, the blue being in all cases perceptibly weakened, probably on account of my having used light of too great a wave-length. I determined therefore to try the effect of light beyond H. It has been already mentioned that the dispersion of the Marlborough Spectroscope increases very rapidly in the violet. With H on the extreme left K occupies the centre, and the spectrum extends considerably beyond the right-hand limit of the field of view. Beginning with the left eye, and using a wide slit, I fatigued the entire retina with the light for about 3 minutes, and then closed the slit until the spectrum became quite invisible. On racking back I found light just perceptible at 1060 scale ($\lambda = 4080$), increasing to a pure brilliant blue at 1002 scale ($\lambda = 4170$).

This pure blue extended as far as 794 scale ($\lambda = 4680$) where green began to be visible. A few seconds' exposure to light from E of ordinary intensity pushed the green back to 750 (= F). I have every reason to suppose that the colour sensation excited under these conditions is a simple primary blue colour sensation unaccompanied by violet, green, or red. In hue it most resembles that portion of the spectrum which lies midway between F and G, but it would be described as much more saturated than a spectral blue of equal intensity. There is no pigment or dye that matches it.

Having thus succeeded in exhausting the violet without affecting the blue, I proceeded to render my right eye blind to blue in order to study the junction of the green and violet.

After about 3 minutes' exposure to strong light from 805 scale ($\lambda = 4630$) I fatigued the retina for about 30 seconds with violet from 1130 scale ($\lambda = 4010$). On partly closing the slit and racking quickly back I came upon the green at 830 scale ($\lambda = 4550$). It was flickering rapidly, alternately surging into the violet and retreating, but always retreating farther than it advanced until it got back again to 794 scale. During this time I kept back the blue by occasional exposures of a few seconds to bright light from 805 scale.

* Neutral, that is to say neither green nor violet. The neutral region between red and blue during green-blindness has quite a different hue. It should be noted that the word is not used to indicate the colour known to artists as "neutral tint," but is rather intended to emphasise the fact that during blue-blindness the green of the spectrum passes into violet through a colour in which there is not the slightest suggestion of blue.

This possibility of postponing the recovery of a colour sensation, when once it has been thoroughly exhausted, by a comparatively short exposure, enables the observer to carry out lengthy observations with a minimum of discomfort.

When the recovery of the violet was complete I exhausted the green sensation with strong light from E, and then, partly closing the slit, racked rapidly across into the violet, finding it now at 770 scale ($\lambda = 4780$). Exposure to red light from between A and B had no effect on the position of the junction of green with violet.

It would appear therefore that when the eye is exhausted for blue, green and violet are found overlapping exactly as red and blue have already been shown to do when the green sensation is abolished. These results show that it is possible to experience each of the four primary colour sensations by itself, unmixed with any of the others.

To the normal eye the part of the spectrum between A and B excites the red sensation only. The part beyond H excites nothing but the violet. The eye, blinded for red, sees pure green from about E to D or even almost to C. And the eye, blinded for violet, sees pure blue from G, half-way to H.

All the colour sensations overlap more or less, except red and violet. Roughly speaking, red and green overlap at D. Red and blue overlap at *b*. Green and blue overlap at F. Green and violet overlap midway between F and G. Blue and violet overlap at G.

It follows therefore that neither blue nor green are visible in their purity except during the states of colour-blindness to violet and red respectively.

I cannot detect any permanent deterioration of my eyesight in consequence of these experiments. It is more than 20 years since I began them, and they have been repeated many times, but I can now trace each colour sensation farther than at first.

These observations appear to me to have a very important bearing on the theory of colour-vision.

I cannot avoid the conclusion that no one colour sensation is related to any other in the sense indicated by HERING. The red and the green are contiguous in the spectrum, but, so far from being antagonistic to each other, they overlap.

Each of them separately or both together can be removed from our consciousness.

The phenomenon of "flickering," described by me in the 'Proceedings of the Physiological Society,'* might seem to indicate that red and green are antagonistic, for we may see them struggling as it were for the mastery. But when we take away the green, the blue and the red are found contending in like manner, and with the same flickering, in another part of the spectrum.

Farther on we have green at its opposite border alternately encroaching on the blue and giving place to it. Farther still the green and violet meet, and there is the same flickering at their junction. Finally the blue and violet overlap in a region which if it is steadily looked at for some time seems blue and violet by turns.

* 'Proc. Physiol. Soc.,' June, 1897.

All these considerations indicate, to my thinking, the absolute independence of each of the colour sensations, and point rather to the theory of YOUNG and HELMHOLTZ than to that of HERING. Moreover, I have entirely failed, though I have sought it carefully, to detect any physical evidence of a separate sensation of yellow.

In all the colour-blind persons I have examined, the so-called "yellow" is spectroscopically identical with other people's green, and the yellow tinge assumed by the red during artificial green-blindness is simply due to the blending with it of the positive after-effect or green dazzle-tint, as I have pointed out.

It will be observed that I have referred to blue as a distinct colour sensation not composed of green and violet. I have come to the conclusion that it is so in my own case, and also in that of many, but not all of those whose colour sensations I have examined.

That there is a distinct change of hue about the neighbourhood of G I have never heard denied by any one who could see H. And the light from that part of the spectrum has a very powerful dazzling effect on all who can see it.

One lady, to whom the green was only comfortably bright, complained that the violet dazzled her eyes, though the slit had not been altered.

Again, the flicker-rate of violet is much slower than that of either blue or red. Red after-images, both negative and positive, die out more quickly than those of any other colour,* whereas to the eye dazzled by violet not only is all that part of the spectrum missing for a long while, but each remaining colour is strongly tinted with violet for several minutes. Moreover, the dazzle-tint of spectral violet dies away without change of colour, if the observer is in a dark room, while that of a mixture of red and blue speedily loses the red and becomes blue long before it has grown much weaker.

I am unable to admit, therefore, that violet is simply blue mixed with red, as MAXWELL thought. Nor can I believe, with YOUNG, that blue can be violet mixed with green, since in the condition of artificial green-blindness I see blue meeting red on the one hand and violet on the other. Moreover, I can exhaust the blue sensation and find violet and green joining in another part of the spectrum. And, finally, I can blind myself to violet and see the spectrum end in a pure blue.

For these reasons, and for those mentioned in my paper on 'Phenomena of Colour-Vision with Intermittent Light,' I consider both blue and violet to be distinct primary colour sensations. But, as I shall show in the next section, there are people to whom a mixture of green and violet may be equivalent to blue.†

* BUFFON seems to have noticed this.

† It would be interesting to examine by my method the case of "blue-blindness" referred to by Mr. NETTLESHIP in his evidence before the Committee on Colour-Vision. 'Proc. Roy. Soc.,' 1892, vol. 51, p. 333.

IV. Examination of the Colour Sensations of 109 People.

During the Summer of 1897 I spent a good deal of time in testing the colour sensations of other people. In all I have examined 109 persons, of whom 5 were known beforehand to be colour-blind. Most of the others were University Extension students attending the Summer Meeting in Oxford.

I used four different methods, namely :—

1. Holmgren's test.
2. The comparison of coloured films.
3. The method of coloured shadows.
4. My own spectroscopic test.

2. *The Comparison of Coloured Films.*

The comparison of coloured films requires a brief explanation. I have found that a certain greenish-blue film, used by makers of Christmas crackers, has a spectrum giving a very dense absorption-band in the red, and that persons looking through it make almost exactly the same mistakes with Holmgren's wools as the red-blind. Moreover, most of the red-blind I have come across find this film almost as colourless as a piece of window glass, describing it as "slightly dingy" or "very pale London smoke." I mount a piece of this, and a pink film with an absorption-band in the green, a yellow which cuts off violet only, and an orange film, separately between pieces of glass, and ask which is the deepest and which the palest colour. People with normal vision select the pink as palest, then the yellow, and consider the orange and blue about equal in depth. Those deficient in violet choose yellow as the lightest shade, while to the red-blind the pink seems a much deeper colour than the blue.

3. *The Method of Coloured Shadows.*

I have employed Hering's coloured-shadow test in the following way. I used half-a-dozen cardboard boxes without lids, blackened inside, with a window of coloured glass at one end, and a white card to serve as a reflector of white light standing up above the box at the other end. The bottom of each was covered with a sheet of white paper on which was laid a wax vesta to cast the double shadow of the colour and its complementary.

The boxes were placed on small tables near the windows of the room. The colours were ruby, amber, signal green, and cobalt glass, a film stained with aniline purple, and a tank of ammonio-sulphate of copper. Each person was asked to write down the names of the coloured shadows, exactly as they appeared, without consulting any one else, it being carefully explained that the private opinion of each individual was desired.

In all, 86 submitted to the test. One gave the following list:—

Boxes.		*Shadows.*
Green	=	blue.
Red	=	(not stated).
Yellow	=	pink.
Purple	=	yellow.
Violet	=	yellow.

He did not complete the HOLMGREN test, but must, I think, have been red-blind.

I was interested to find that the same divergence of opinion, with regard to the colours of some of these shadows, obtained, when they were first studied, in the middle of last century. BUFFON describes the shadows cast by the light of a red sunset as green inclining to blue, and only pure blue when the light near the horizon was yellow, as at a clear sunrise. BEGUELIN, writing in 1764, 22 years later, disputes this statement, saying that he always saw the coloured shadows blue, and not green, unless he made them fall on yellow paper.

A good many people seem to have taken part in the discussion, and opinions were pretty evenly divided. MAZEAS speaks of the "blue and red" shadows cast by a candle and the moon, which, however, is only a modification of OTTO DE GUERICKE'S old experiment, "Sic potest mane, tempore crepusculi, umbra plane cœrulea in charta alba produci, quando nimirum inter suppositam chartam et accensam candelam digitus vel aliud quid ita tenetur ut umbram super chartam projiciat, tunc umbra ista non nigra sed perfecte cœrulea apparebit."*

Here, however, the light of the candle may very well be considered orange-yellow, the complementary colour of which is generally acknowledged to be blue. In my own case ordinary red glass gives a pure blue shadow by daylight and a greenish-blue shadow by lamplight. But to several of my friends the shadows are greenish-blue and green under these circumstances.

It will be seen from the results of the coloured-shadow test that this divergence of opinion is probably due to a difference in relative sensitiveness of the colour sensations.

ANALYSIS of Results of the Coloured-Shadow Test.

Ruby glass.

Colour of shadow by daylight:

Blue, 21; blue-grey, 12; grey, 9; green, 15; green-grey, 7; blue-green, 17.

Making in all 42 who saw no green in it, against 39 to whom it was more or less green.

* "Experimenta Magdeburgica."

Green glass.

Colour of shadow by daylight :

Neutral tint, 1; blue, 1; red, 2; claret, pink, rose, magenta, "violetty-pink," 17; violet, purple, lavender, lilac, heliotrope, 55.

Amber glass.

The colour of the shadow by daylight was described by 62 as blue-grey, and by 24 as more or less lavender or violet in tone.

Blue (cobalt) glass.

The shadow by daylight was described by all as yellow or greenish-yellow.

Purple film (aniline stain).

The shadow by daylight was green.

Violet solution (ammonio-sulphate of copper).

The shadow was described by all as yellow.

4. *Examination of the Colour Sensations of Seventy Persons with the Spectroscope.*

In using the spectroscopic method for testing the colour sensations of other people I have modified it for obvious reasons. Instead of producing temporary colour-blindness, I simply fatigue each colour sensation in turn in so moderate a degree that the subject is quite unconscious of the change.

The observer is directed to close or open the slit until the spectrum has that degree of brightness which he considers most comfortable and pleasant to look at. He is next told to turn the rack and examine the spectrum from end to end, calling attention to each change of hue as he comes to it. He is especially asked to find the pure yellow.

Many people seem surprised at the lack of pure yellow in the spectrum, and are therefore instructed to place behind the pointer the part where yellow ought to be.

Others see a great deal of yellow, and are asked to select the purest part, which tends neither to green nor red. Having found this colour, they are desired to remember it.

The spectrum is then set so that nothing but the pure red is visible, and the observer is told to look steadily at it for 30 seconds, and at a given signal to turn the rack steadily but quickly until the same pure yellow comes behind the pointer. After the scale-reading has been taken, the E-line is placed in the middle of the field, looked at for 30 seconds, and the rack turned till the first beginnings of the blue reach the pointer. He is next made to gaze at the blue just beyond F for 30 seconds, and then requested to find the violet.

After this he seeks the extreme limit of the visible spectrum in the violet, using a shortened slit so that the edge of the spectrum may be more easily seen, and opening the slit a little if he prefers to do so.

Then he begins to work back again, fatiguing the eye for 30 seconds each time, but still keeping the slit only wide enough to give the degree of brightness he considers most comfortable, and not altering it while seeking the next change of hue. After looking at violet he finds where blue begins, after blue he seeks the green, and after green the red. Finally he looks for the limit of the spectrum at the red end.

The chief points to be insisted on are, (*a*) that the eye must be fatigued for exactly the same number of seconds each time, and (*b*) that the first impression of each colour is what is wanted, and that second thoughts are not best.

In order to make this clear it is well to allow the observer to look again after the scale-reading has been taken, and see how much the colours have changed. Most people are greatly interested in this phenomenon, and quickly enter into the spirit of the thing. Many of those I tried went over the spectrum twice, stopping within two or three scale divisions of the same place each time, although the instrument was placed out of focus so as to hide the Fraunhofer lines.

Seventy-five people were examined in this way. Of these, five were known beforehand to be colour-blind. Among the rest, one or two were rather weak in the violet, but all passed HOLMGREN's test easily.

The following example shows how the results are entered during the examination.

No. 48. Bright sunshine. Highest eye-piece. Fatigue for 30 seconds each time.

After red, green begins at	581,
,, green, blue begins at	682,
,, blue, violet begins at	872,
Violet * ends at	1328.
After violet, blue begins at	863,
,, blue, green begins at	767,
,, green, red begins at	616,
Red ends at	492.
Normal position of boundary between red and green . .	606.

In this case all the space between 581 and 616, viz., 35 scale divisions, is occupied by both red and green, and looks green when the red colour sensation is diminished in intensity, and red when the green is fatigued. For brevity I term this the *red-green overlap*.

To such an eye there is a good deal of yellow in the spectrum. The pure green extends from 616 to 682, where blue begins to show, and the *blue-green overlap* is

* H = 1200, and K = 1260, so that this is well beyond K, but the graduation is not reliable beyond this.

from 682 to 767. Beyond this, from 767 to 863 is pure blue, and, beyond the blue, violet up to 1328. But there is a curious uncertainty about the blue and violet, which do not overlap, so far as these measurements go, but show a space between of 863 to 872 = 9 divisions. As no apparent diminution of luminosity in this portion of the spectrum was mentioned by the observer, it is a little difficult to explain the discrepancy. It occurred rather frequently in the blue and violet, and in some cases with all the colours. It may perhaps be partly due to lack of training. Few people, except those used to the spectroscope, are familiar with true violet, all the violet dyes and flowers containing red as well, and the lack of this in the spectral colour inclines some to regard it as a kind of blue.

Taking the average of seventy, whose colour sensations may be considered normal, I obtained the following figures (see Plate II., fig. 12):—

Red	extends from	498	to	638 = 140,
Green	,,	597	,,	755 = 158,
Blue	,,	693	,,	878 = 185,
Violet	,,	835	,,	1193 = 358,

so that

Red and green	overlap from	597	to	638 = 41,
Green and blue	,,	693	,,	755 = 62,
Blue and violet	,,	835	,,	878 = 43.

That is to say, in wave-lengths

Red	extends from	λ 7606	to	λ 5510,
Green	,,	λ 5930	,,	λ 4840,
Blue	,,	λ 5170	,,	λ 4430,
Violet	,,	λ 4540	,,	λ 3975.

In reality each colour sensation extends so much farther that red and blue overlap, and so do green and violet, the only two colours which I have not proved to do so being red and violet. But this method represents the amount of change brought about by looking at colours of ordinary brightness, such as flowers in sunshine, and may therefore be considered to afford some indication of the extent to which our ordinary judgments of colour are affected by contrast.

An examination of the individual cases shows that they may be divided broadly into two classes, viz., those whose colour sensations as measured by this process overlap, as in the following instance:—

No. 60—

Red = 492 to 646; green = 587 to 764,
Blue = 700 to 950; violet = 830 to 1275,

and those whose colour sensations do not overlap, such as

No. 8—

Red = 516 to 600; green = 600 to 750,
Blue = 748 to 897; violet = 897 to 1077.

The first class included several amateur artists, a manufacturer of encaustic tiles, persons engaged in textile industries, and ladies given to fancy work—in fact, those whose occupations require skill in comparing colours.

Between the extremes of both classes there were many graduations. Of the whole number, five belonged to the extreme form of the second class, making none of the colours overlap. Three failed with the red-green only, and three others with the blue-violet as well as the red-green. Fifteen failed to make blue and violet overlap, but succeeded with the other colours. Altogether, 29 failed to find the overlap in one or more of the mixed colours.

The totals for each pair were as follows:—

Blue-violet	26	failures,
Red-green	11	,,
Green-blue	8	,,

Amongst those of Class I. were several who found a greater overlap of the red and green than of the green and blue, and *vice versâ*. For example:—

No. 55—

Red, 500 to 633; green, 601 to 761. Overlap = 32.
Blue, 701 to 926; violet, 810 to 1176. Overlap = 116.

No. 56—

Red, 502 to 645; green, 596 to 760. Overlap = 49.
Blue, 730 to 865; violet, 833 to 1191. Overlap = 32.

It was noticed that in sorting HOLMGREN'S wools No. 55 had discriminated shades of blue that were alike to No. 56, but No. 56 had sorted the yellows more easily than No. 55.

There were a good many instances of this characteristic difference in the power of judging colours, and in most cases the amount of the overlap seemed to afford an indication of the development of the faculty.

In order, if possible, to detect any relation that might exist between the several colour sensations, I plotted all the results upon a chart, arranging them in the order of the extension of the red into the green. In many cases a short red was accompanied by a short violet, and also by a general diminution of the overlap in all the colours. There were, however, some notable exceptions. Among those of the first class were four remarkable cases, which may throw some light on the history of the theories of colour-vision.

No. 31, No. 33, and No. 62 made the green and violet overlap, so that to them there could be no pure blue, while No. 36 not only made green and violet overlap, but also blue and red, so that both the pure green and the pure blue were absent. In my own case this only occurs after exposure of the eye to a very bright blue or green light, as in the experiments on artificial colour-blindness.

Bearing in mind that five others of the second class found no overlaps at all, so that to them the mixed colours were absent, it is interesting to compare these results with the data given by some of the earlier experimenters before the theories of colour-vision had crystallized into their present form.

WOLLASTON, who observed a narrow slit through a prism, found the spectrum to consist of four colours—red, green, blue, and violet—which occupy spaces in the proportion of 16, 23, 36, and 25 respectively, making 100 for the whole length. He says the colours differ scarcely at all within these limits. He attributes the narrow line of yellow to the mixture of the red with the green light, and seems to have found the mixed tints of blue with green and of blue with violet comparatively insignificant.

About 10 per cent. of those I examined resembled WOLLASTON.

On the other hand, Sir ISAAC NEWTON'S colour sense appears to have been more highly developed. Even without using a narrow slit by placing his screen at a sufficient distance and employing a second prism the spectrum he obtained may have been tolerably pure. To him orange, yellow, and indigo were sufficiently important to rank as colours. And it was so with quite half the cases I examined.

YOUNG, on the other hand, may have had colour sensations corresponding with either of the following :—

No. 31—

Red, 510 to 609 ; green, 599 to 785.
Blue, 723 to 790 ; violet, 779 to 1075.

No. 52—

Red, 490 to 632 ; green, 586 to 797.
Blue, 701 to 972 ; violet, 816 to 1260.

No. 31 had according to these figures absolutely no pure sensation of blue, and very little overlap between red and green.

No. 52, a science lecturer, had a well-developed overlap between red and green, but so very little pure blue left free between green and violet (less than $2\frac{1}{2}$ per cent.

of the visible spectrum), that it could not have been noticed with such means as Young possessed.

And Young says*: "It is certain that the perfect sensations of yellow and of blue are produced respectively by mixtures of red and green, and of green and violet light, and there is reason to suspect that those sensations are always compounded of the separate sensations combined—at least this supposition simplifies the theory of colours; it may, therefore, be adopted with advantage until it be found inconsistent with any of the phenomena."

I submit that this simplification, probably valid enough in the case of Young and of several people examined by me, is not permissible in my own case, and in that of a good many others, in whom the blue sensation is well defined and separate.

A colour sensation may escape detection either because it is so little developed as to produce an insignificant effect, or because the colours on either side of it overlap each other so as to leave no part of the spectrum for which the intensity of the colour sensation in question exceeds the sum of the intensities of the other sensations which overlap it.

Examples of the first kind are frequent among the red-blind, and I suggest that Young may have been an instance of the second. Mixtures of green and violet would represent pure blue to such an eye. Suppose, for example, that the part of the spectrum, which in my own case excites probably 96 per cent. blue, 2 per cent. green, and 2 per cent. violet sensation, produces in another observer 50 per cent blue, 25 per cent. green, and 25 per cent. violet. To him a mixture of equal parts of a blue-green producing 50 per cent. blue and 50 per cent. green, with an indigo producing 50 per cent. blue and 50 per cent. violet, would, when the intensity was reduced to one-half, be identically equal to the purest blue he is capable of perceiving, while to me it would be a mixture.

It is evident that too large an overlap of the colour sensations in the spectrum must involve a diminution in the power of perceiving them separately.

I have already given some of the reasons why I cannot agree with Maxwell that violet is not a simple colour sensation. He says†: "the extreme ends of the spectrum are probably equivalent to mixtures of red and blue, but they are so feeble in illumination that experiments on the same plan with the rest can give no result."

Clearly he saw a difference of hue in the spectrum at this part, but mistook it for a slight tinge of red. But violet differs from blue as to its physiological properties, not in the same direction as red does, but in its exact opposite in every respect. Real violet, to those who are sensitive to it, has a peculiar dazzling effect, even when mixed with other colours, which is not possessed by blue, still less by red. Almost without exception, those who could see beyond K (24 out of 70) remarked on this peculiar brilliancy of the violet.

* 'Lectures on Natural Philosophy,' vol. 1, p. 439, edition of 1807.

† 'Phil. Trans.,' vol. 150, 1860, p. 78.

MAXWELL'S colours, as far as they go, agree fairly well with the average of the 70 persons I examined.

Transition point between—

Red and green, MAXWELL λ 5837 ; BURCH (average of 70 persons) λ 5730 ;
Green and blue, „ λ 5003 ; „ „ „ „ λ 5003 ;
MAXWELL, blue-indigo λ = 4498 ;
BURCH, blue and violet λ = 4480 ;

Pure colours—

MAXWELL, red = λ 6309 ; green λ = 5287 ;
blue = λ 4574 ;
BURCH (average of 70 persons) red = λ 6250 ; green λ = 5250 ;
blue = λ 4710 ; violet λ = 4150 ;

Thus his blue is intermediate between my average blue and average violet.

The general conclusion to be drawn from this spectroscopic examination of the colour sensations of 70 people is, I think, that the individual differences, whether of education or of physiological condition, or both combined, are considerable, and capable of accounting for some of the differences of opinion with regard to colour-vision.

But in counting the number of the colour sensations, surely it is most reasonable to accept all those of which we can obtain physical or physiological evidence, although they may not be detected with equal ease by all observers. For this reason I advocate the recognition of blue as well as violet among the colour sensations.

I am unable, in my own case, to detect the existence of a separate yellow. That may be because I do not possess it. But, if it exists, it makes up the total number of colours to five, four of which I certainly have. It is true that the red, the green, the blue, and the violet of my yellow spot are all situated farther towards the refrangible end of the spectrum than the corresponding colour sensations of the rest of the retina.*

If while looking at the yellow of the spectrum I suddenly open the slit, I see for a moment or two an oval or round patch—according to the power employed—of brighter light, moving up and down according to the direction of my eyes, and refusing to quit that part of the spectrum. This is probably associated with the yellow spot, like MAXWELL'S dark patch in the blue-green, only his was due to a defective colour sensation, while mine appears to be the contrary. I can easily conceive that in some cases this phenomenon may be developed to such an extent as to constitute a yellow sensation.

HERING'S black-white sensation I have not found. But the evidence for and against it is of a somewhat different character, and I propose to discuss it in a separate paper.

* BURCH, 'Journal of Physiology,' vol. 21, p. 430.

Cases of Colour-Blindness.

No. I.

Was conscious of his peculiarity, and keenly interested in the examination of it. With Holmgren's wools he made the usual mistakes of the red-blind. His description of the general appearance of the spectrum was as follows :—

Beginning with the red, he called the light between B and D "yellow." This colour continued without alteration of hue to 736 scale (= λ 4940), where it changed to "rose." I then asked him to trace the "rose" as far as he could distinguish it, using the arc-light. He did not notice any alteration of hue till he reached the bright calcium lines (H), which he described as "very bright—a heavenly blue—darker than the blue sky."

Asked what colour he would add to "rose" to make it of the same hue as the calcium line, he said, "Probably more blue."

Returning from the blue end of the spectrum slowly towards the red, he stopped at 550 scale (= λ 6550), saying that there was some slight difference in hue of the "yellow" at that point.

The end of the spectrum he placed at 520 scale (= λ 7090).

It may be noted here that during artificial red-blindness a pink rose looks exactly the colour of the spectrum just beyond F, and the blue sky looks violet.

After familiarising himself with the appearance of the spectrum, he went through the system of testing described in the previous section, repeating the measurements several times, first after thirty seconds' fatigue, and afterwards with an exposure of two or three minutes.

After red from B to C—*

Change of hue in the "yellow"	591	(30 seconds).
,, ,, ,, ,, ...	593	(1 minute).
,, ,, ,, ,, ...	606	(3 minutes).

After green at E—

"Yellow" changes to "rose"	717	(30 seconds).
,, ,, ,, ...	705	(about 1 minute).
,, ,, ,, ...	685	(3 minutes).

After blue, just beyond F—

"Heavenly blue" begins	861	(30 seconds).
,, ,, ,, ...	825	(about 3 minutes).
,, ,, ends	1263.	

Working back again,

* This part of the spectrum partially fatigues the green in my own case. Hence the result with the three minutes' exposure. See page 8. This spectrum was not bright enough beyond B.

After violet, between G and H—

The beginning of "rose" was not well marked.

After blue, from G half-way to F—

"Yellow" begins at . . . . 725 (30 seconds).
" " " . . . . 744 (about 2 minutes).
" " " . . . . 748 (about 3 minutes).

After green, between E and B—

"Yellow" changes in hue at . . . . 550 (30 seconds).
" " " " . . . . 603 (3 minutes).
" " " " . . . . 610 (about 3½ minutes).

The spectrum ends at 520.

His "change of hue in yellow" corresponds to a weak red, his "yellow" is the green of normal vision, while his "rose" is identical with our blue, and his "heavenly blue" with violet.

The mean positions of his colour sensations are therefore as follows :—

	Red.	Green.	Blue.	Violet.
No. I.	585	669	723	1044
Average of 70 persons . . .	568	676	785	1014

The extent of each of his colour sensations is :—

	Red.	Green.	Blue.	Violet.
No. I.	90	157	176	438
Average of 70 persons . . .	140	158	185	258

And the amount of overlap is :—

	Red-green.	Green-blue.	Blue-violet.
No. I.	19	63	36 (indefinite)
Average of 70 persons	41	62	43

It was evident, however, that the *intensity* of his red sensation bears a very much smaller proportion to that of the green than these figures would lead us to suppose, since bright scarlet and deep red-brown appeared alike to him, and he matched mauve with magenta. Still it was evident that he had some slight sense of red.

My greenish-blue film, referred to on p. 17, appeared to him very pale, but appreciably affected his judgment of HOLMGREN'S wools. I also found that he could distinguish some shades of red by gaslight, which were alike by daylight.

In my paper on "Certain Phenomena of Colour-Vision with Intermittent Light,"* I have pointed out that when light is admitted to the spectroscope in short brilliant flashes at the rate of about 23 per second, a subjective absorption-band appears between C and D, and at the same time the red between B and C becomes brilliantly luminous.

Judging it possible that this method might enable him to see red, I arranged the apparatus for the purpose, using the single-prism spectroscope with the slit horizontal, and a wide-angled low-power eye-piece, set so that the red was well in view rather below the middle of the field, which included the whole of the part he called yellow, and a little of his "rose colour" (= blue).

I set the disc revolving rapidly, and asked him to look steadily at the spectrum and describe anything special which he might notice in it, meanwhile allowing the speed to slacken gradually. After about a minute, he saw the flicker pattern referred to in my paper, and began to describe it. Suddenly he said, "Look and tell me if I am right—do I see anything below the yellow ?"

I asked him not to take his eye away, but to continue looking whilst the speed of the disc was still further reduced. Then he said, "Oh, now I see sunset colour."

He also found the violet relatively much brighter with flashing light, and seemed to learn the difference between it and blue. He afterwards drew the spectrum as he saw it in coloured chalks, selecting mauve, light blue, yellow ochre, and light red, the two latter being chosen for lack of brighter colours.

Some accidental remark led me to suspect that the yellow spot was less sensitive to red than the rest of the retina. I therefore placed a red lamp and a candle about two feet apart on the table of the dark room. Looking at the red light he said it appeared yellow, but not quite so bright as the candle. But while looking straight at the candle he was conscious of a change of hue in the flame of the lamp, which became "sunset colour."

No. II.

Is apparently red-blind. My greenish-blue film he described as of a "very pale green like a dirty cover-glass." It made scarcely any difference in the appearance to him of HOLMGREN'S wools. He matched violet with magenta and scarlet with rich green. Tested with the spectroscope, after looking at red light near C for 30 seconds he found a change of tint to "blue" at 718, and on a second trial at 715 (= λ 5040).

After fatiguing the eye with blue he found a change of hue at 930 (= λ 4310), but thought it not well defined. The spectrum ends for him in the violet at 1155

* 'Journal of Physiology,' vol. 21, p. 430, 1897.

(= λ 3990). Working back from the violet he found "blue" change to "yellow" at 747 (= λ 4880). Pressed to describe the colour, he said, "Yellow or red—I can't say which—it may be red or may be yellow."

He failed to notice any farther change of hue in the "yellow" between this and the end of the spectrum, which he placed at 527 (= λ 6950). But after looking steadily for some time at light from E he found a change of hue on the red side at 583 (= λ 6090). On the same occasion he placed the limit of the spectrum at 522 (= λ 7060).

With flashing light he thought there was a difference at the red end. It was "a little darker," but he did not seem to recognise any different colour. Evidently he has less of the red sensation than No. I., and his violet is much weaker, not extending as far as the H-lines. The two colour sensations which are best developed in his case are spectroscopically identical with the blue and green of ordinary people, although he calls them blue and "red or yellow."

No. III. and No. IV.—I desire in this place to acknowledge my indebtedness to this gentleman (No. III.) and his brother (No. IV.) for the very thorough and careful series of observations which they made for me. They did not confine themselves to the method of fatigue for 30 seconds with moderate illumination, but, as will be seen, used also the wide slit, producing a considerable degree of temporary green-blindness.

No. III.

This case differs in several respects from the two previous ones. With HOLMGREN'S test the same mistakes are made, reds and greens being confounded, and violets matched with magenta. By the method of coloured shadows the following results were obtained :—

Red Glass.—This glass appears to him so dark as to give no coloured shadow unless the white card reflector is very much reduced in area. The shadow is then "blue" on a "yellow" ground. The colour of the glass is given as "red" or "dark yellow."

Green Glass.—Is called "yellow" and evidently appears much less dark than the red. The complementary shadow is "a better blue," and the white card reflector is used.

Amber Glass.—Is "of the same colour, but a shade more yellow." The shadow is "a still better blue—sky blue."

Yellow Film.—Is "a lighter colour—bright yellow." The shadow is "a darker blue—greyer—the colour of Silurian paper."

Cobalt Glass.—Is "blue," and the shadow "yellowish-white."

Violet Solution (Ammonio-Sulphate of Copper).—Is "a darker blue than the blue glass, but of the same hue." The shadow is "yellowish."

The first hint of a difference between No. III. and Nos. I. and II. was obtained with the blue film, which was at once recognised as a fairly strong colour, two thicknesses of blue being considered about as deep as four of the eosin film. This same blue, to Nos. I. and II., was scarcely distinguishable from colourless glass. It was evident, therefore, that his eyes must be more sensitive than theirs to light from between B and D.

Spectroscope Tests. (Arc-lamp. Spectroscope used with the highest eye-piece.)

A. General Appearance of the Spectrum.

The red is considered a "dullish yellow," and extends as far as A. The green is "a brighter yellow," and passes into "blue" about 730 (= λ 4970). The "blue" becomes darker at 995 (= λ 4190), and the spectrum ends about 1092 (= λ 4050) with sunlight, but he was perfectly able to see the bright lines of calcium H and K in the arc-light.

B. Fatigue Experiments with Slit of Constant Width.

After blue at 820 for 30 seconds, "yellow" begins at 752 (= λ 4855).

After orange at D for 30 seconds, "blue" begins at 702 (= λ 5110).

No change of hue could be detected in any part of the "yellow" by this method.

C. Fatigue for 30 seconds with Wide Slit.

Subsequent Observation with Narrow Slit.

After light from E, using the right eye, a change in the yellow at 606 (= D).

To the left eye the field appeared of the same colour throughout, viz., "a very good yellow," but to the right eye there was for some minutes "a distinction of colour on the two sides" of the D-lines.

After light from B, a change of hue to "yellow" at 571 (= λ 6220).

D. Observations with Direct Sunlight.

The B-line was selected as marking the division between "dark yellow" and "muddy colour." The "muddy colour" ends at A.

N.B.—With some absorption spectra in which the greater part of the red and orange is cut off, I myself see, after looking for some time, a dirty brown border to the green on the red side. This might very well be described as "muddy colour," and is due to the feeble traces of red not being sufficiently bright to form an orange.

E. Examination by Flashing Light.

With the apparatus already referred to he at once saw three well-marked regions of colour in the field of view, viz., "red" from A to about D, or a little beyond, then "yellow" as far as b_4, passing into "blue" at about F. The rest of the spectrum was out of sight.

He called my attention to a phenomenon evidently connected with the yellow spot. The junction of "blue" with "yellow" was not a straight line, but the "blue" appeared to bend down in one part to meet the "yellow," the apparent dimensions of the bend corresponding, as far as could be judged from his sketch, with those of the yellow spot.

In my own case each of the four colours, red, green, blue, and violet, shows a similar bend, but in the opposite direction, each colour extending farther towards the more refrangible end of the spectrum for the yellow spot than for the rest of the retina.* I have met one or two cases like my own. MAXWELL's peculiarity in this respect has been already mentioned.

No. III. seemed doubtful whether "red" should be called a distinct colour, but he perceived it whenever the proper speed was attained, losing it again if the disc went too fast or too slow.

Summary.

His "yellow" has on one side the same limits as the normal red, and on the other side the same limits in the spectrum as the green of normal colour-vision. I consider it, therefore, as compounded of red + green. But these two elements of the sensation are relatively abnormal as regards intensity. His green extends farther into the red than the average green, and his red is so much weaker that he only distinguishes it as "muddy colour" (? brown). His blue, also, is strong, but his violet, though of normal extent, is weaker than my own.

No. IV.

Came with his brother on December 4, 1897, and both went through all the tests independently. In matching coloured wools no difference could be detected between them. By the method of coloured shadows the following results were obtained by No. IV. :—

(1.) *Red Glass.*—The direct light was considered light brown, and the complementary shadow light blue.

(2.) *Amber Glass.*—Direct light yellow, complementary shadow a slightly darker blue than No. I.

(3.) *Green Glass.*—Direct light darkish yellow, complementary shadow a dull blue.

(4.) *Cobalt Blue Glass.*—Direct light a brilliant dark blue, complementary shadow a washed-out or pallid yellow.

Spectroscopic Examination.

He describes the red end of the spectrum as a "deepish yellow." At 713 (= λ 5050) it changes to blue, and at about G it becomes "a better blue." He

* 'Journal of Physiology,' vol. 21, p. 430.

compares violet to "the colour of the Mediterranean Sea, or the Italian sky," but considers blue to resemble "the colour of the winter sky." With this description his brother entirely agrees.

After looking at "yellow" (*i.e.*, green at E) for 30 seconds, blue begins at 702 (= λ 5110).

After looking at blue (between F and G) for 30 seconds, "yellow" begins at 734 (= λ 4940).

After dazzling the eye for some time with brilliant light from E, using a wide slit, and then observing a spectrum of moderate intensity, he found "smoke" begin at 528 (= λ 6930) and end at 508 (= λ 7310). He defines "smoke" as being the colour of the sun through a London fog. His brother on this occasion made "smoke," which he had described before as "muddy colour," begin at 551 (= λ 6530).

As sunlight was not available, we had recourse to the arc-lamp, and found that they both saw the bright calcium lines (H and K) easily, but could not trace the continuous spectrum quite so far. Experiments with flashing light were tried, but not very successfully, as the arc-lamp was not working well.

There seems to be very little difference between the two. In both the violet is not markedly strong, but certainly not below the average. There seems to be a certain amount of red sensation, but not sufficient to render it an important element of vision. I hope, when I have procured the necessary apparatus, to make measurements of the relative intensity of the various parts of the spectrum as they see it.

Summary of Conclusions.

1. By exposing the eye to coloured light of sufficient intensity a condition may be produced closely resembling colour-blindness, in which for a time one or more of the colour sensations are practically abolished.

2. Artificial colour-blindness differs in degree only from the condition of retinal fatigue induced by looking at any brightly-coloured surface.

3. There are four colour sensations, namely, red, green, blue, and violet.

Red-blindness is produced by light from B;
Green-blindness by light from between E and *b*;
Blue-blindness by light half-way between F and G;
Violet-blindness by light from between H and K.

4. There is no special colour sensation of yellow. Yellow results either from the simultaneous excitation of the green and the red sensations, or from the action of a weak red light during the positive after-effect of green.

5. Blue is not a mixture of green and violet, for blue and violet are both visible during green-blindness, and green and blue are both visible during violet-blindness.

6. Violet is not a mixture of blue and red, for the violet is unaltered either in hue or in luminosity during red-blindness.

7. HERING'S theory of a red-green sensation is not supported, but rather contradicted, by these experiments. During temporary red-blindness the sensation of green is not intensified, and during temporary green-blindness the sensation of red is not intensified. Moreover, blindness to red and blindness to green can be produced simultaneously.

8. During artificial colour-blindness the hue of feebly-illuminated objects is more or less strongly modified by admixture of the positive after-effect of the colour by which the retina has been fatigued.

9. Any two of the above four colour sensations may be simultaneously abolished without affecting the remaining two, except as indicated in the preceding paragraph.

Light from	D	produces	blindness to	both	red and green ;
,,	F	,,	,,	,,	green and blue ;
,,	G	,,	,,	,,	blue and violet.

10. During blindness to blue and violet the eye may be further blinded to red, leaving only the green colour sensation, or it may be blinded to green, leaving only the red sensation. In both cases, especially the latter, the positive after-effects are very strong.

11. The two eyes may be simultaneously blinded each to a different colour sensation.

12. There is considerable variation in the relative intensity of the four colour sensations in different individuals. Partial violet-blindness is not infrequent.

13. Cases of colour-blindness may be easily diagnosed by the method of fatiguing the retina described in the paper.

14. The results obtained by the Author are unfavourable to the theory of HERING, and confirm that of YOUNG and HELMHOLTZ, but indicate the existence of a fourth colour sensation, namely, blue. This, it should be noted, YOUNG was prepared to admit, if experimental evidence of it should be found.

EXPLANATORY NOTE TO PLATES 1 AND 2.

(Note added March, 1899.)

The paintings of the spectra from which the plates have been reproduced were specially prepared for that purpose after the paper had been authorised for publication, the "blinding" process being gone through afresh in each case. This necessarily involved considerable delay in the publication of the paper.

In the reproduction of the spectra, it has been thought desirable to avoid the use of colours known to be fugitive. Hence the violet of the spectrum has been represented throughout by the conventional mixture of blue and red, although such a mixture has less spectral violet in it than the blue alone, and produces, in my own case, a sensation quite different from that excited by the spectrum between G and H. I had hoped it might be possible to employ a pigment said to be stannate of cobalt, the tint of which is much nearer to a true violet, but am informed that, as at present manufactured, it cannot be used for printing.

Some explanation may also be desirable with regard to the lower tone of the green where it passes into the blue on the one hand and the yellow on the other. The green selected is one of which the spectrum extends as little as possible into the blue and the yellow, and the blue chosen reflects but little green light. Consequently the smallest overlap in printing produces a darker shade. If this is remedied by mixing white with the blue, it gives that portion of the spectrum a pink tone by contrast, and if the green is diluted with white a muddy appearance is produced. I have not yet found a pigment which will serve for the transition tint without revealing itself as a separate colour. The same difficulty, though to a less extent, is met with in the transition from green to yellow, and in printing it is strongly marked where the ends of the spectrum fade into a background of the complementary colour.

Figs. 1 to 10 are described on pp. 7 to 10.

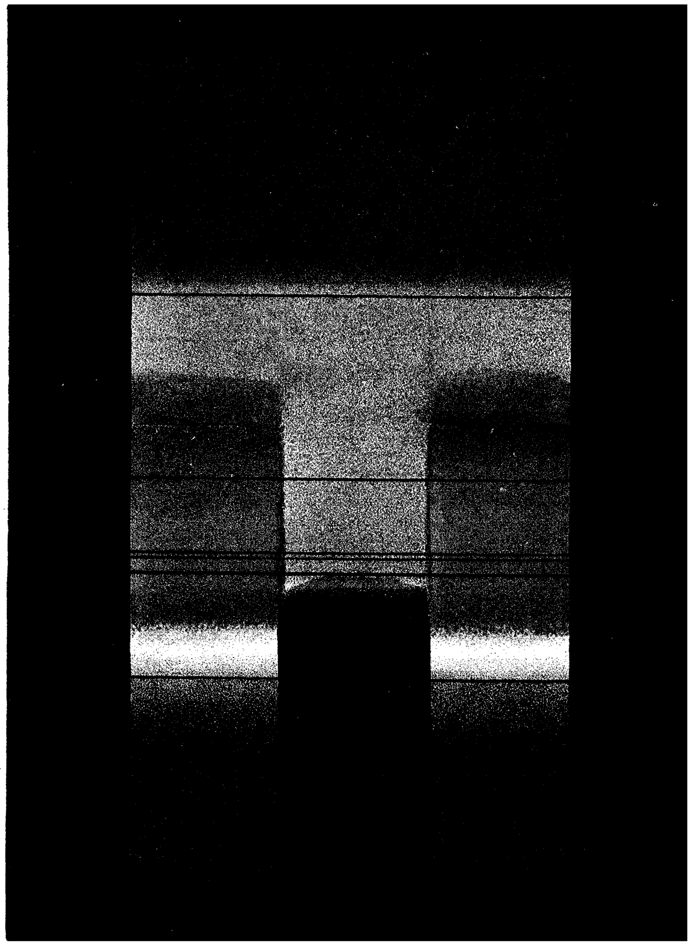
Fig. 11 is described on pp. 12 and 13.

Fig. 12 is described on p. 21.

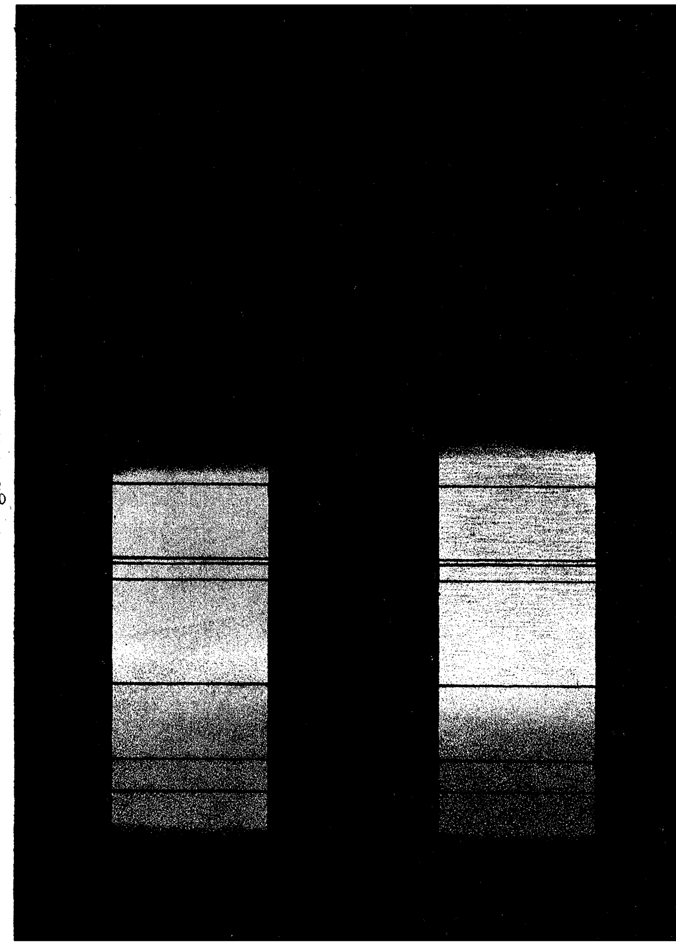
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Phil. Trans. B. Vol. 191. *Plate* 1.

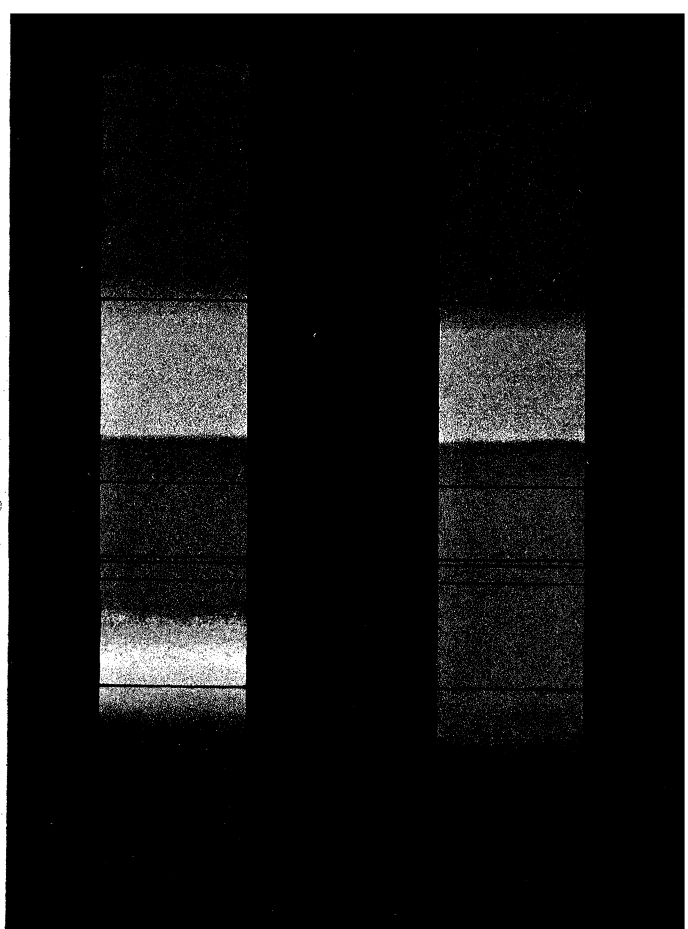
Fig. 3.



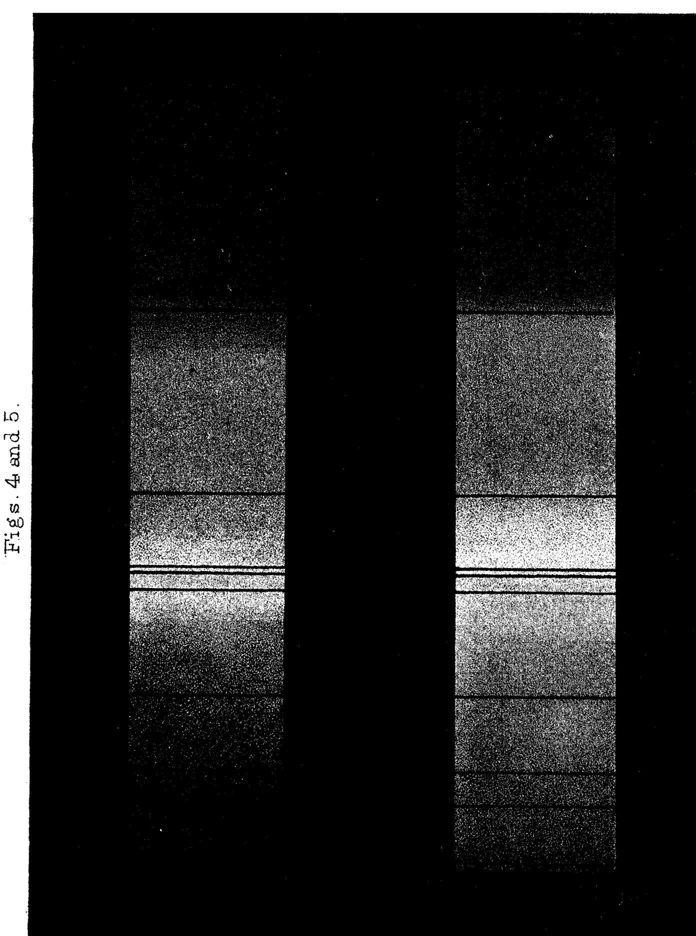
Figs. 6 and 7.



Figs. 1 and 2.



Figs. 4 and 5.



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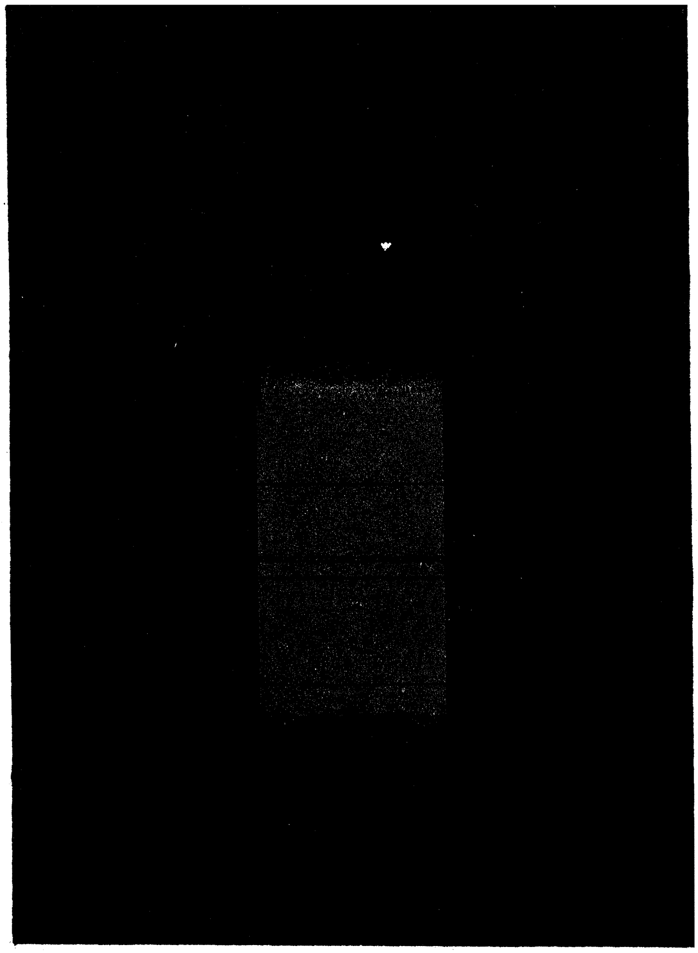
West, Newman chromo.



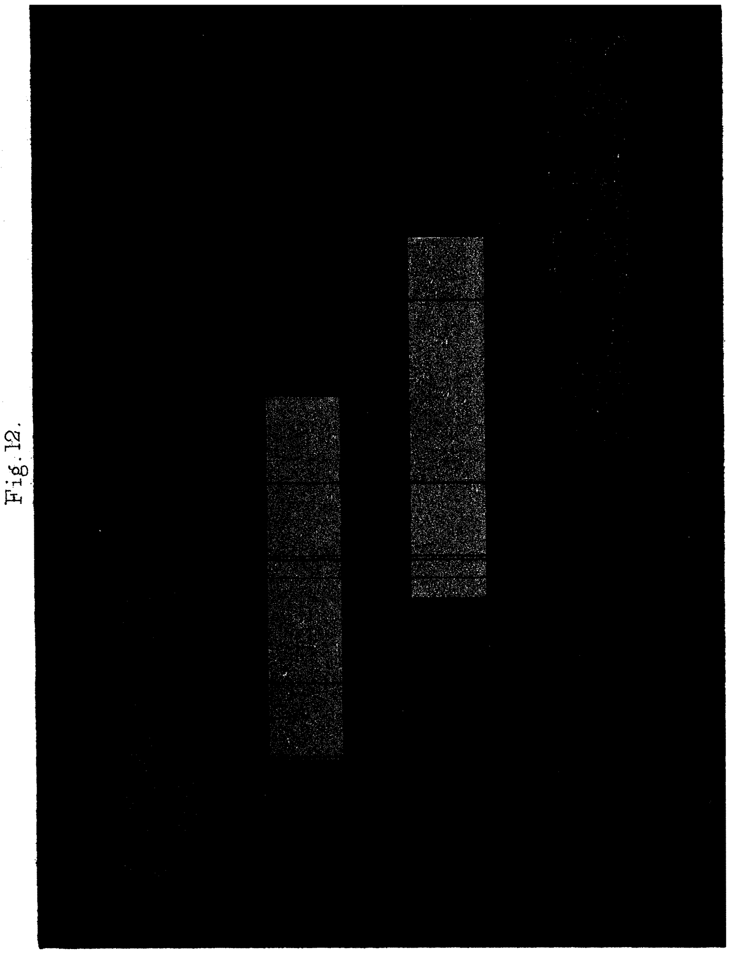
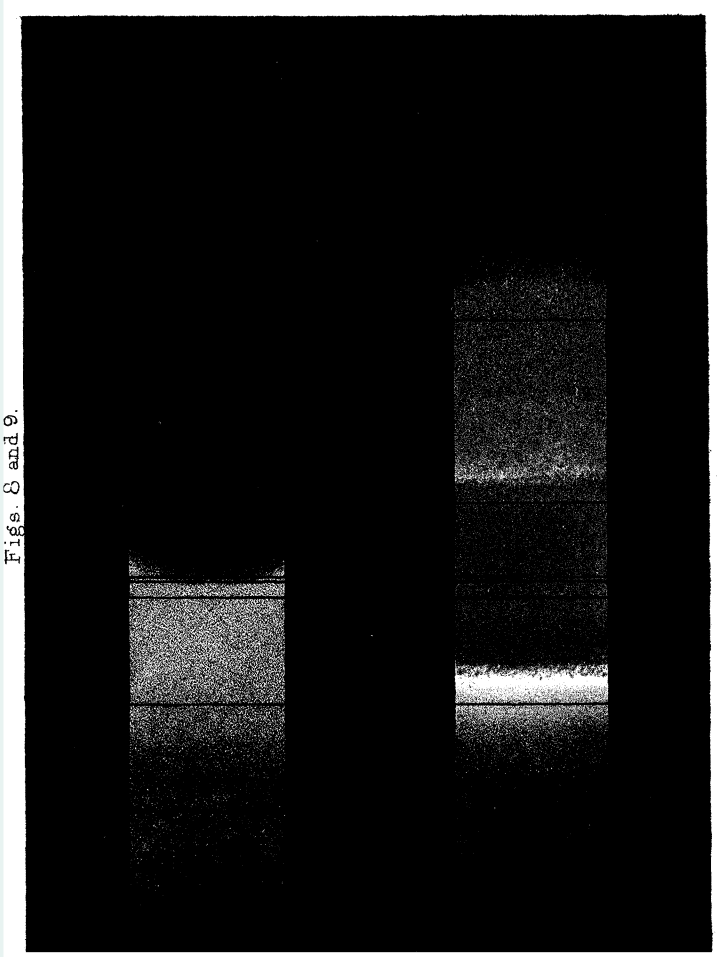
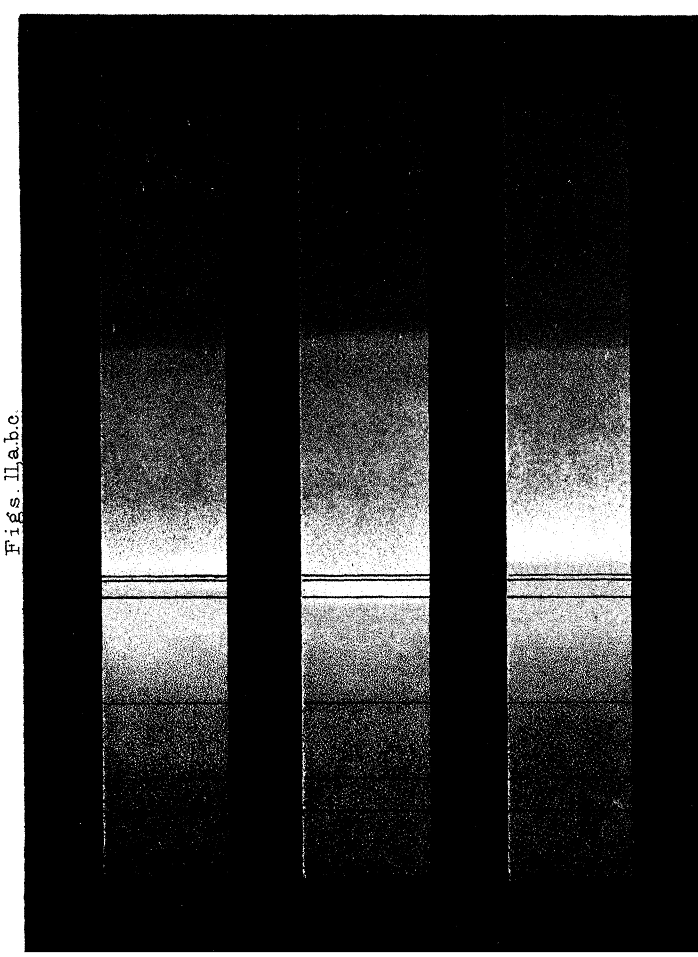


Fig. 12.



Figs. 8 and 9.



Figs. 11 a.b.c.

West, Newman chromo.

Figs. 1 and 2.

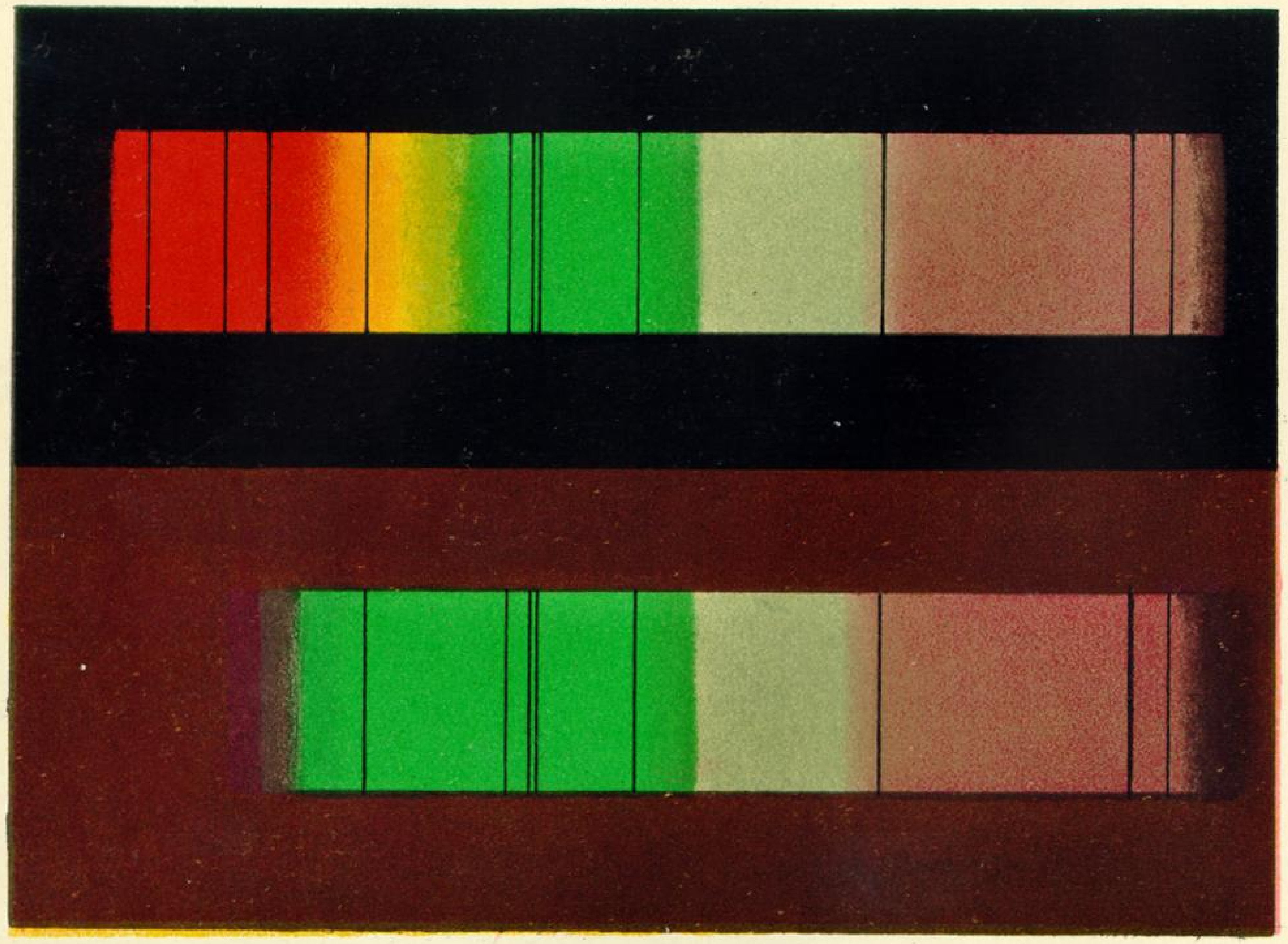
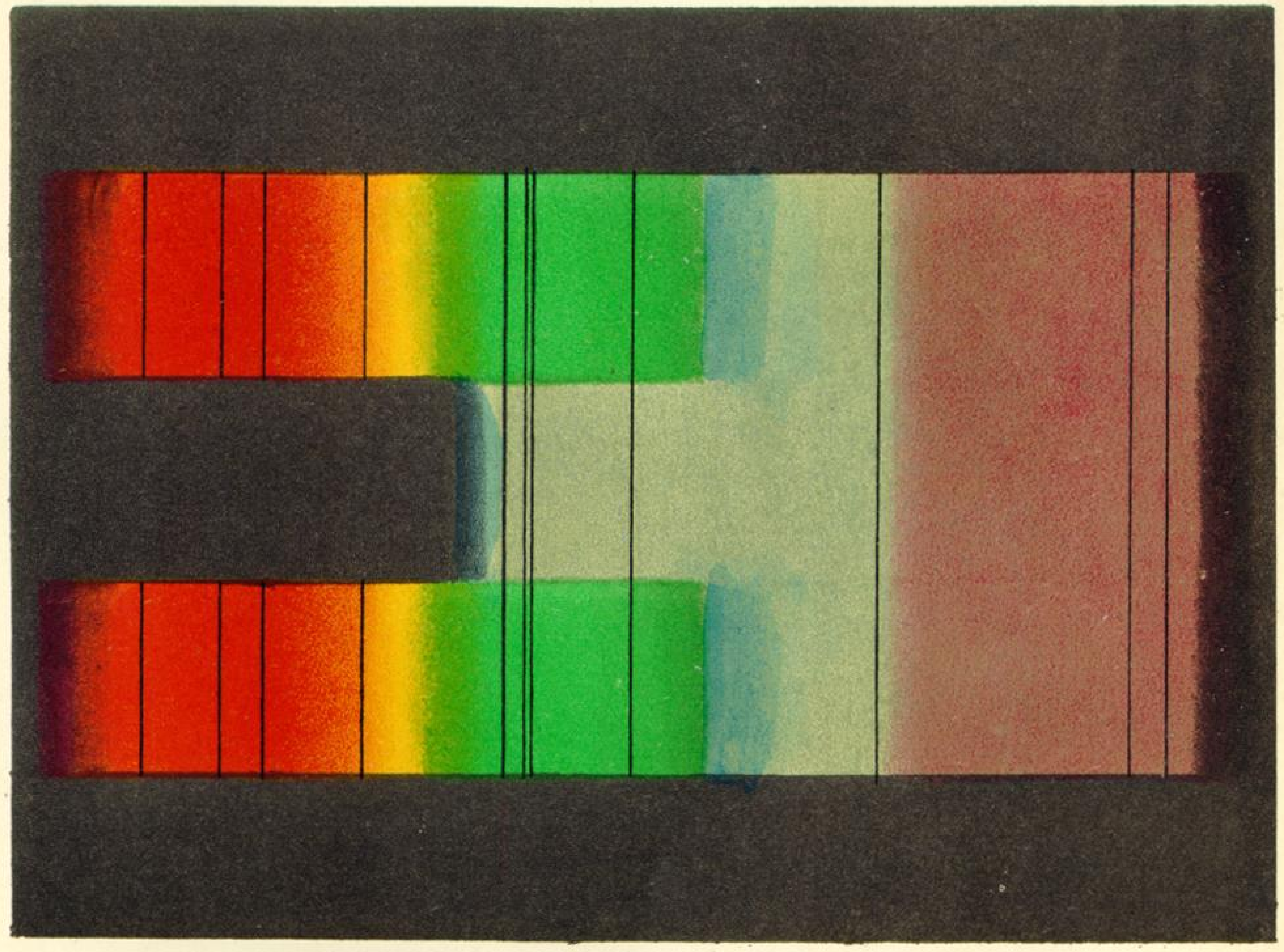
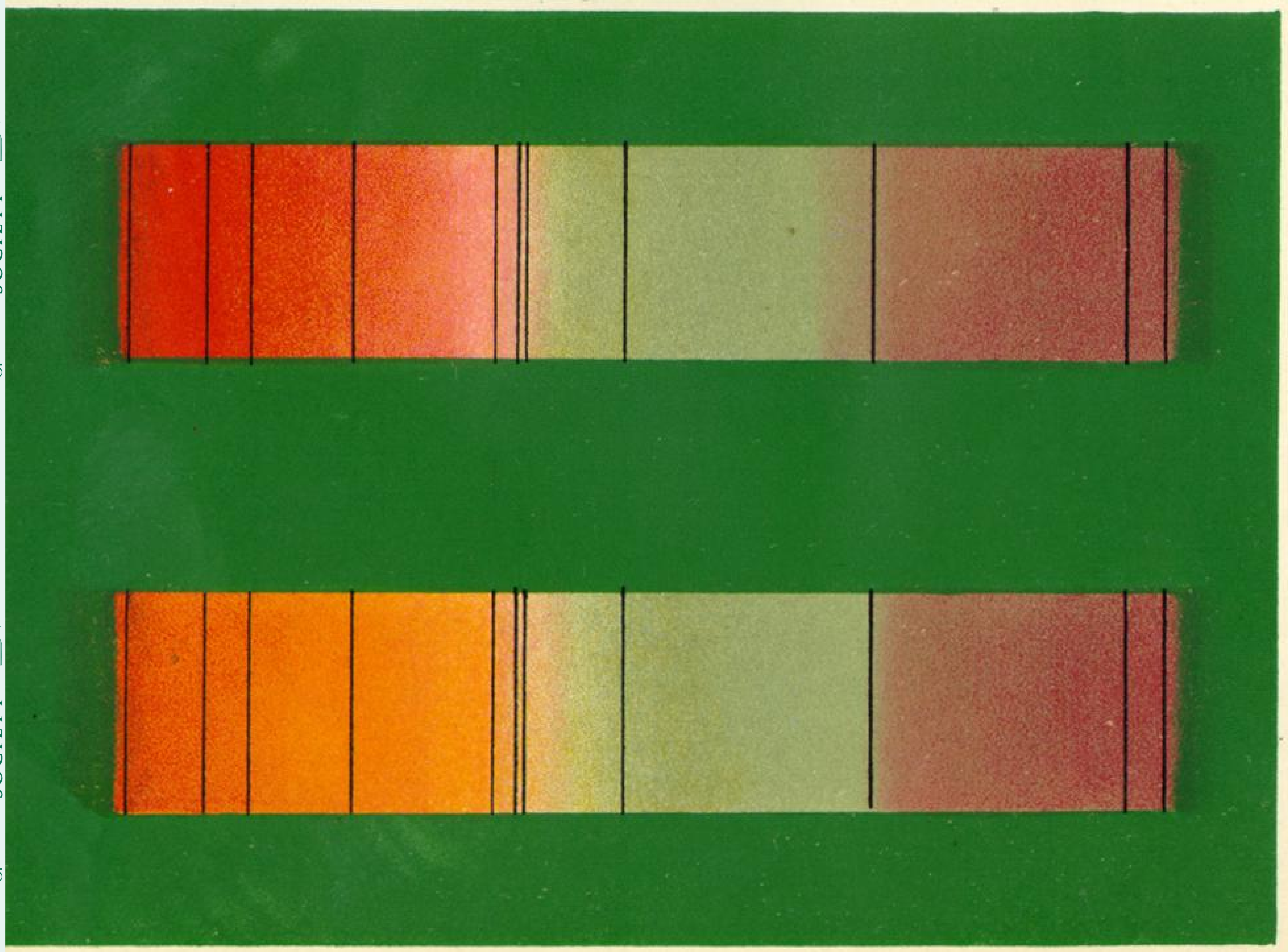


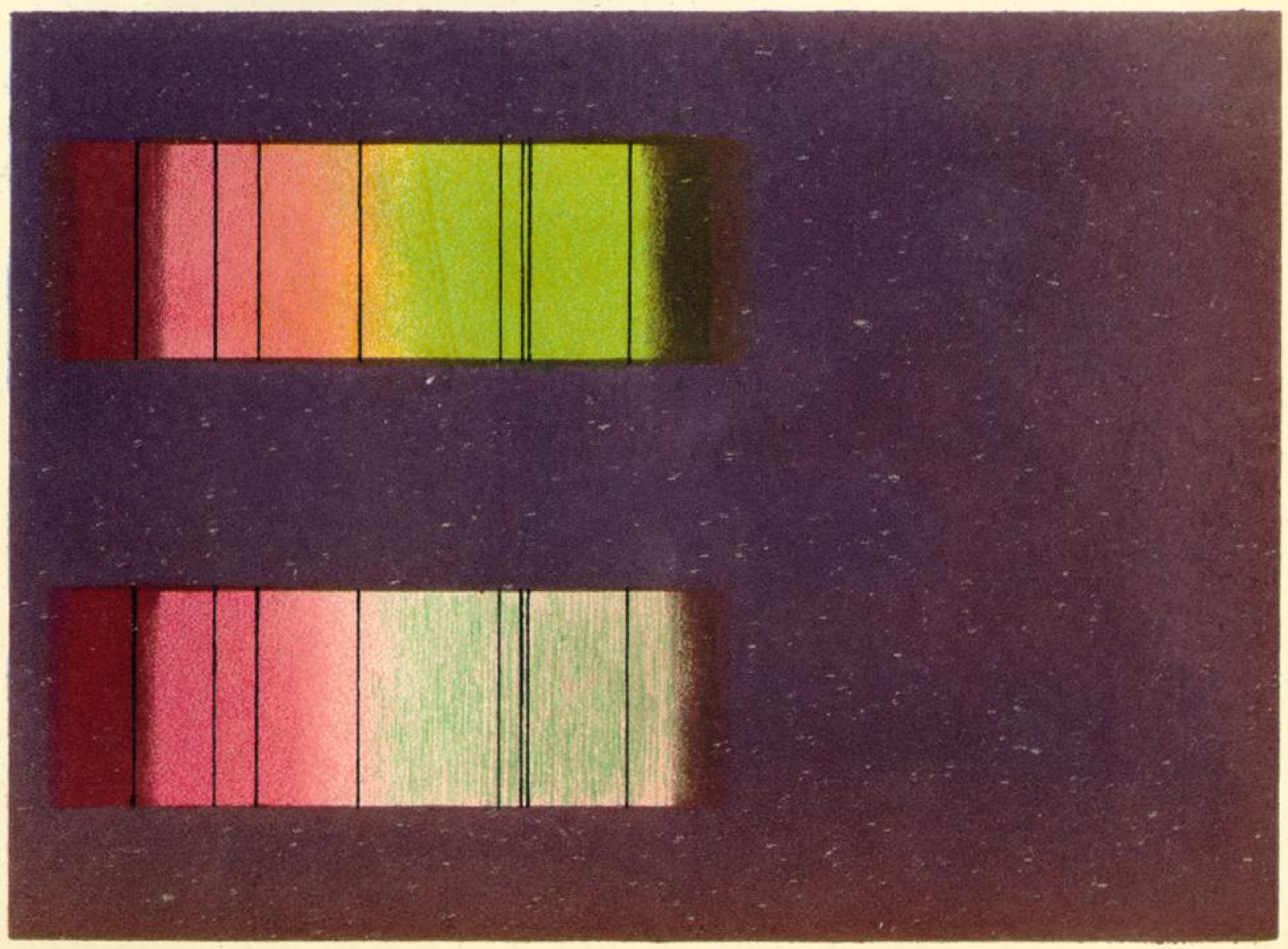
Fig. 3.



Figs. 4 and 5.



Figs. 6 and 7.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Figs. 8 and 9.

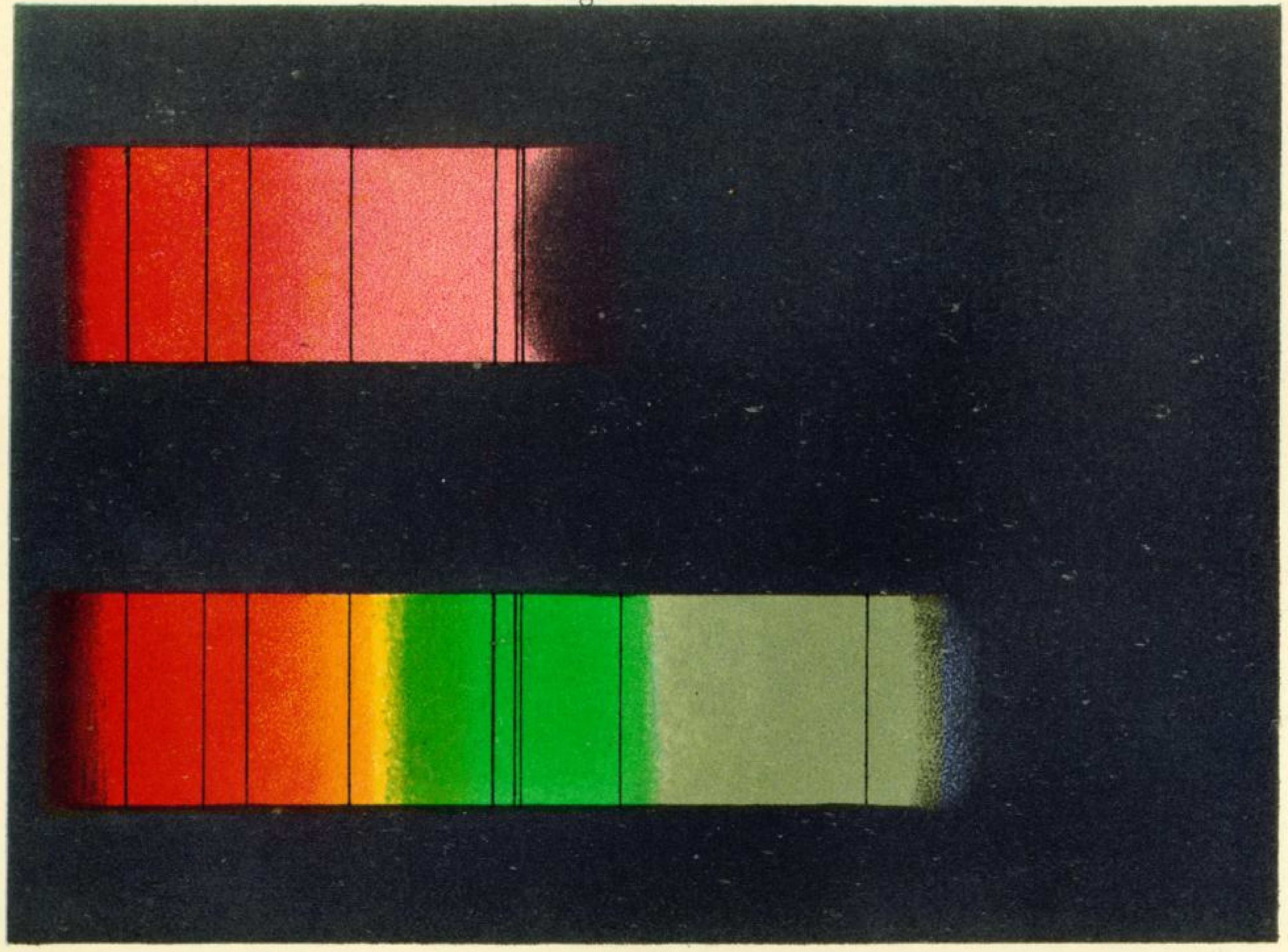
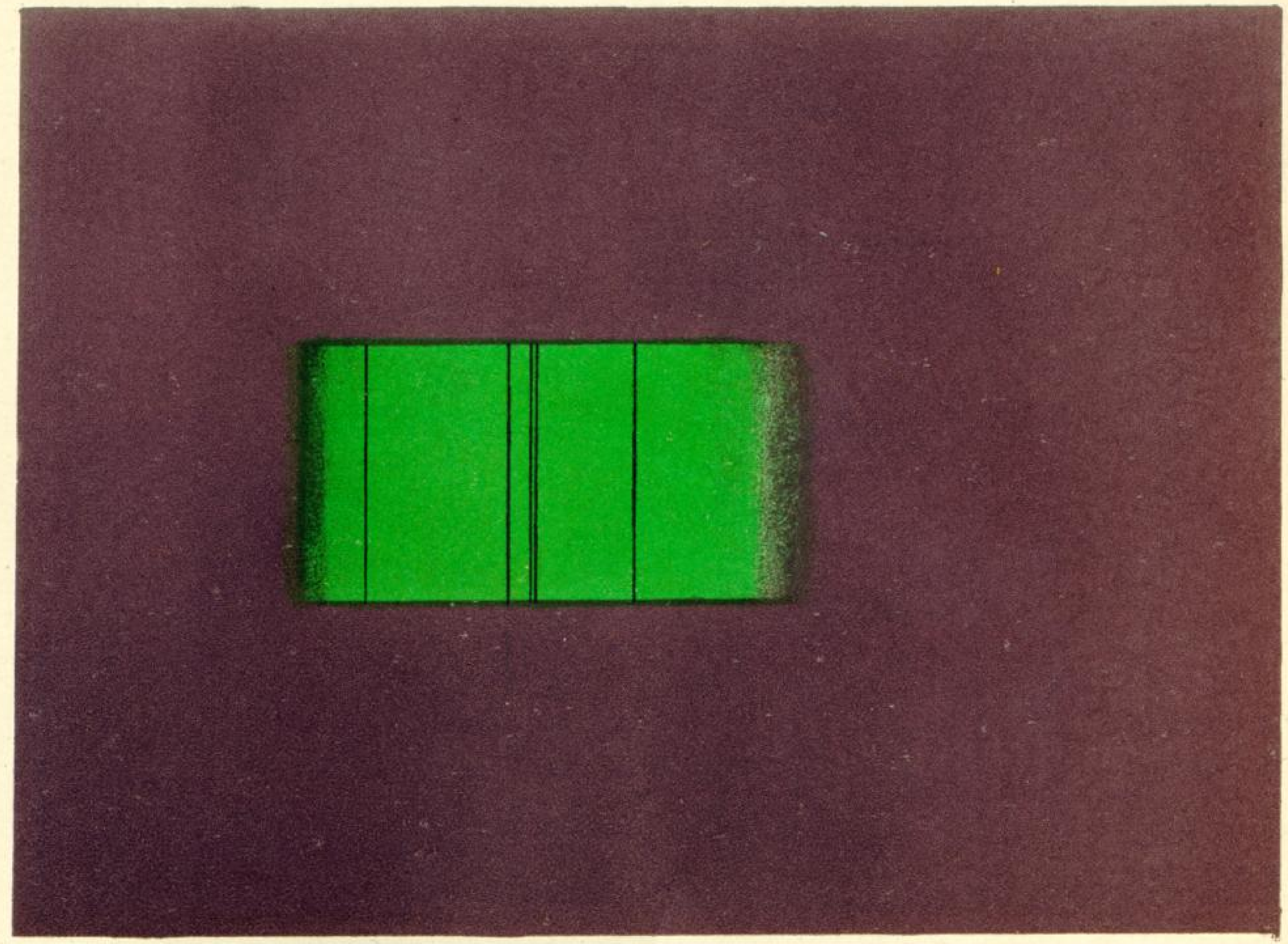


Fig. 10.



Figs. 11,a.b.c.

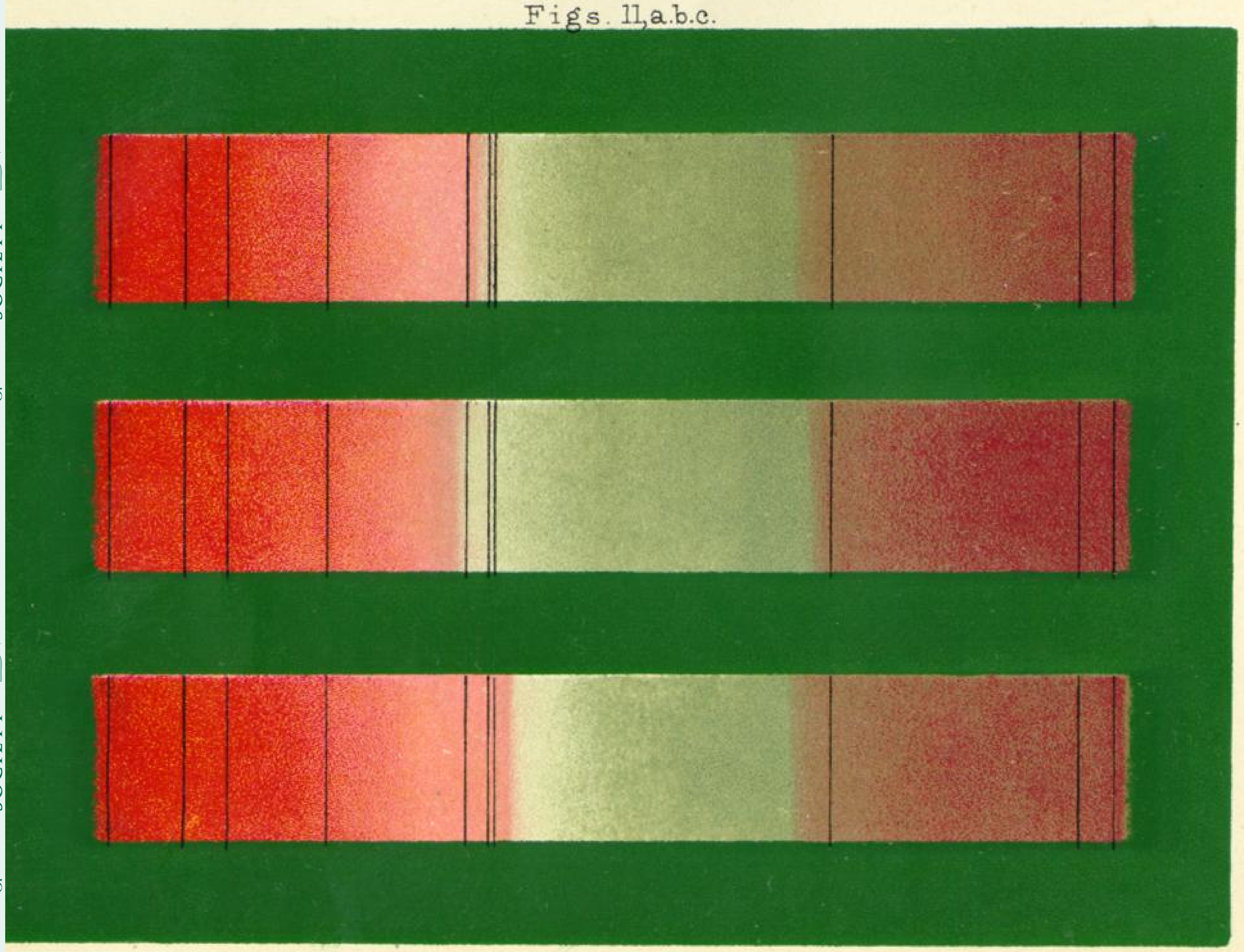
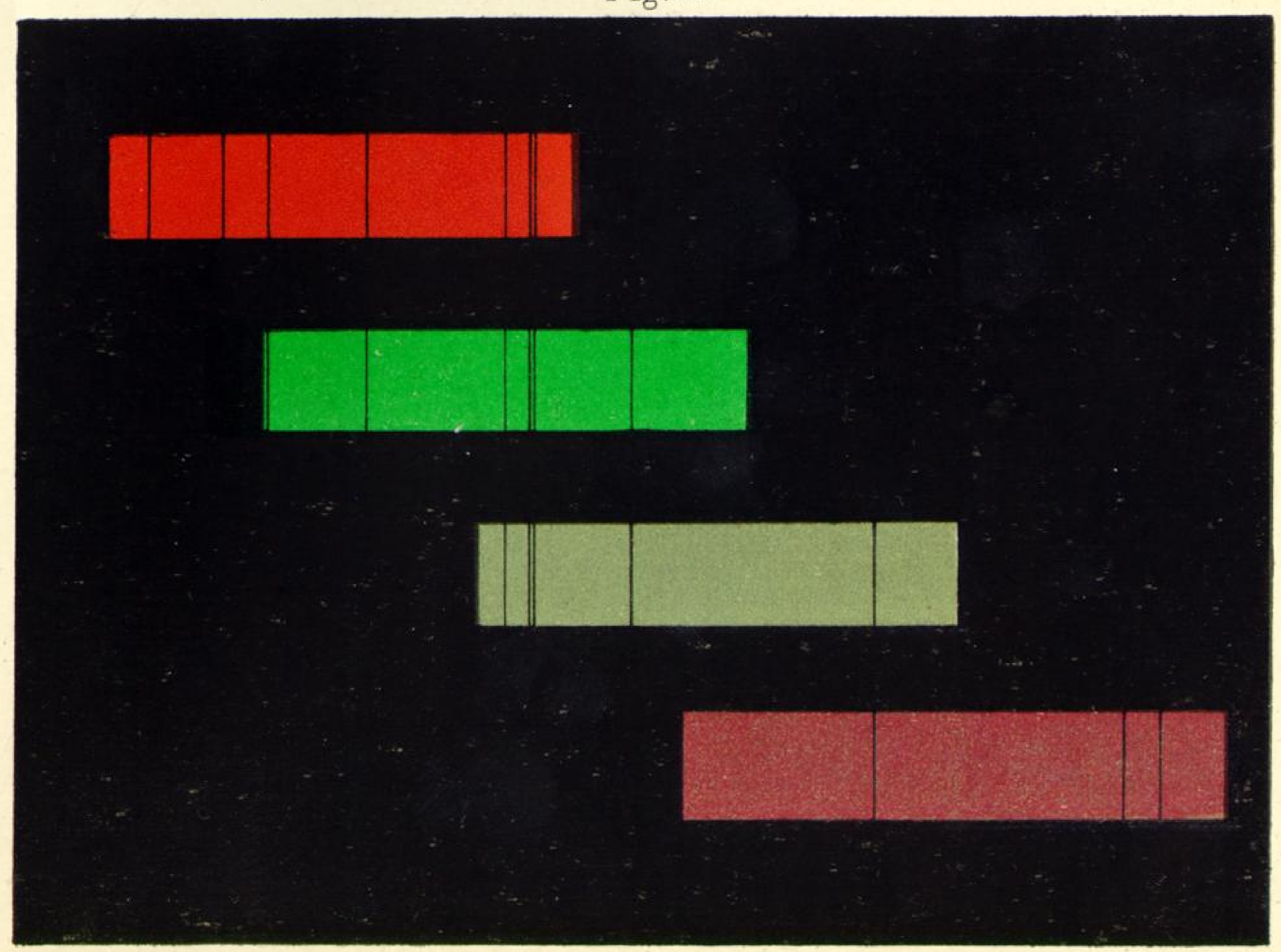


Fig. 12.



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