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Physics. — "*Regular consequences of irregular refraction in the sun.*" By Prof. W. H. Julius.

The images produced on our retina, or in the focal plane of a telescope, may be considered as geometrical projections of light-emitting objects. Our idea of the object, as derived from the shape of the image, is founded on the validity of that rule. If it fails to hold, if, for instance, the rays are curved in traversing a whirling mass of air, so that they no longer form homocentric beams, the distribution of the light in the focal plane will give us a false idea of the object. What we then observe is no "image".

We cannot possibly doubt that rays, in passing through extensive gaseous parts of celestial bodies, deviate from the straight line in an irregular way. If caught in a telescope, such rays do not form an image of the source of light. Yet our conclusions regarding distribution of matter, and other local conditions in the sun, have to be deduced from the phenomena visible in the focal plane. In interpreting those phenomena we therefore are compelled to account for the probable course of the rays inside the celestial body considered.

Most investigators of solar phenomena have so far never thought this necessary. Sun-spots, faculae, flocculi, prominences, are spoken of as if they were luminous "objects" from which our telescopes show us the geometrically projected "images". This includes the *supposition* that the curving of the rays in the sun is too insignificant to have any considerable influence on the phenomena.

Astrophysicists, of course, cannot be ready to abandon their unlimited belief, that they are dealing with optical images of real objects, unless very strong evidence of the contrary be given. Indeed, at first sight such loss of confidence in familiar forms would seem to deprive us of almost every hold on the solar phenomena, and to doom all our notions to vagueness. But the step must be taken nevertheless, and we will try to show that the new way leads *not* to vagueness, but, on the contrary, to concise notions, by which the correlation of the principal solar phenomena can be clearly represented.

On the degree of refraction probably existing in the solar atmosphere.

We imagine the sun to be an incandescent mass, surrounded by a gaseous envelope, which we shall call the "solar atmosphere". Whether the latter passes gradually or abruptly into the main body, does not matter for the present. The constituents of the atmosphere may be thoroughly mixed, but the average composition and density of the mixture will vary along the radius. *In this paper we shall only deal with the influence which the selectively absorbing mixture of gases, constituting the solar atmosphere, exerts on the white light, emitted by the lower layers of the sun.* Perhaps there exist local accumulations of separate gases: we leave that possibility out of consideration now; nor shall we notice the fact, that selective radiation by the solar atmosphere may in a perceptible degree contribute to the sun-light observed.

Besides in the direction of the radius the density is sure to vary also in other directions, and that in an irregular way, on account of the movement of the gases. The point in question is: can we reasonably admit the existence of density gradients sufficiently great to produce any considerable refraction effects?

If irregular density gradients comparable in magnitude with the vertical gradient of our terrestrial atmosphere near the surface $\left(\frac{d\Delta}{ds}=16\times10^{-10}\right)$, occur in the sun, the distribution of the light over the solar disk must already be quite perceptibly influenced thereby. Indeed, in gases we have the approximate relation [1])

$$\frac{d\Delta}{ds}=\frac{1}{R\varrho}$$

between the gradient $\frac{d\Delta}{ds}$, the refraction constant or specific refracting power $R=\frac{n-1}{\Delta}$, and the radius of curvature ϱ of rays perpendicular to the gradient. Let us suppose the average value of R in the mixture not to differ too much from 0,5, then our equation gives $\varrho=1.25\times10^{9}$ c.m.; which means, that the radius of curvature of rays, propagated at right angles with the supposed gradient, is less than one fiftieth part of the radius of the photosphere ($r=7\times10^{10}$c.M.). Even within a relatively thin chromospheric layer the light coming from lower levels may therefore alter its direction very sensibly.

This inference holds *a fortiori* for layers, in which the pressure is several atmospheres, because there the gradients too are likely to exceed the one assumed.

And the importance of ray-curving increases greatly again with waves belonging to the nearest vicinity of absorption lines. Such waves suffer anomalous dispersion. With them the refraction constant of the absorbing gas may be several hundred times greater than

[1]) Proceedings Roy. Acad. Amst. IX, p. 352; Astroph. Journ. **25**, p. 107 (1907).

0,5, and therefore, even if that gas occupies only a small percentage in the mixture, so that its density gradients too are but a small percentage of those of the atmosphere, even then the light in question will be more strongly curved than normally refracted rays. Its radii of curvature will be very small indeed as compared with the radius of the photosphere; and much lesser gradients than the one assumed would already suffice to produce very marked refraction effects with such waves.

On the influence of a local rarefaction or condensation in the solar atmosphere on the distribution of the transmitted light.

In fig. 1 (Pl. I) SS' represents a part of a central section of the photospheric surface. Whether in that surface we meet with a physical discontinuity in the condition of matter, or not, is of little consequence in the following argument. Perfectly opaque it is not likely to be; so we may safely presume that an external point M receives more light along the direction ab than along other directions cd, ef, gh.[1] Let an observer be stationed at a great distance in N. We imagine the atmosphere $S\,Q\,Q'\,S'$ to have a uniform density throughout, except in the neighbourhood of M. At that point the density may be a *minimum* (case A) or a *maximum* (case B), and from there gradually pass to the uniform value on all sides. Let us suppose the gradient to be greatest in the space between the two little circles. Fig. 1 refers to case A. Rays leaving the surroundings of M in the direction MN have suffered an incurvation there, the concave side of which faces the regions of greater optical density, and, therefore, is turned away from M. From a distant point N one will observe a certain distribution of brightness, determined 1. by direction and magnitude of the density gradients, and 2. by direction and intensity of the light entering our region of unequal density. A rigorous solution would require a knowledge of the density in each point, and of the intensity corresponding to each direction of incidence; but it is not difficult to discern, that the main result must always be as follows: In the middle the rarefied region shows the intensity of the back-ground as seen in the direction fe; towards the edge m_1 the brightness will first increase, because we meet with rays emerging radially from the photosphere (direction ab); furtheron it will perhaps decrease (direction cd); but it certainly

[1] This presumption is supported by considerations to be stated afterwards (cf. the foot note on p. 280).

must be very small near te edge m_2, from whence only rays, not coming from the photosphere, can reach the observer.

Our rarefied region, though perfectly transparent, thus looks like an object emitting at the left side less, at the right more light than the back-ground.

If in those parts of the atmosphere, which surround our rarefaction, the density were not perfectly uniform, the distribution of the brightness within the region considered would be modified, to be sure, but not so much as to change the main character of our result.

From case A we deduce as a general rule:

A relatively small region in the solar atmosphere, where the density passes through a minimum, and which, as seen from the earth, is projected excentrically on the solar disk, will show *darker* than the surroundings on the side *opposite* the centre of the disk, and may be *brighter* than the surroundings on the side *facing* the centre, the latter peculiarity however requiring, that the distance from the centre be not too small.

If the rarefaction is projected near the centre of the disk, it will show a dark rim on all sides.

Let us now consider the course of the light through a small region, enclosing a *maximum* of density (case B, fig. 2). Again the rays bend in such a way that their concave side is turned toward the places of greater optical density, that is, now, towards M. [1]) Examined from N, the region round M gives the impression as if there were an object, emitting at the left side more, at the right side less light than the back-ground.

From case B we deduce the rule:

A relatively small region in the solar atmosphere, where the density passes through a maximum, and which is seen excentrical on the solar disk, will show *darker* than the surroundings on the side *facing* the centre of the disk, and may be *brighter* than the surroundings on the side *opposite* the centre, provided the distance from the centre be not too small.

If the condensation is projected near the centre of the disk, it will show a dark rim on all sides.

In our scheme we supposed the region of smaller or of greater optical density to be approximately spherical. In order to make sure whether the above rules always represent the main character of the

[1]) If in both cases A and B the density gradients had the same absolute values, the rays would generally change their direction more in B than in A, because in B they are curved in the same sense as the levels of equal density, and therefore travel a longer way through the non-homogeneous region.

distribution of brightness, also when the arrangement of the density gradients is less simple or even very irregular, we may supplement the inquiry by making a few simple experiments.

Some experiments with curved rays.

A saturated solution of common salt has at 15° the specific gravity 1.204; just as great is the specific gravity of a mixture of 78 parts of pure glycerine with 22 parts of water. A drop of one of these liquids keeps floating in the other for a considerable time, but gradually dissolves. Owing to the great viscosity of the rather strong solution of glycerine, no fast convection currents occur in this process: the chlorure of sodium and the glycerine diffuse into each other.

The index of refraction of the glycerine solution for yellow light being 1.44, that of the salt solution 1.38, the optical density will rapidly fall off in the layer where diffusion takes place. Rays may bend there with a radius of curvature of only a few millimeters. Suppose e. g. the layer in which diffusion takes place to be at a certain moment 0.02 cm. thick, then we get for the average value of $\frac{dn}{ds}$

$$\frac{1.44-1.38}{0.02}=3,$$

and for the radius of curvature

$$\varrho=\frac{n}{\frac{dn}{ds}}=\frac{1.41}{3}=0.47 \ cM.$$

So these liquids enable us to imitate the irregular ray-curving in the solar atmosphere, and thereby to preserve approximately the same proportion between the radii of curvature of the rays on the one hand, and the dimensions of the source of light on the other hand, if we only give the latter a diameter of some centimeters.

The experiments were made as follows.

Against the back of a vessel of plate-glass was placed a diaphragm with a circular opening, covered with ground-glass. A set of large strongly converging lenses formed the image of an arc light of 3 amp. at a distance of about 6 cm. behind the centre of the opening in the diaphragm. The ground-glass thus became a circular source of light of which the brightness gradually decreased from the centre towards the edge.

Let the vessel be first filled with our solution of glycerine. We force a drop of salt-solution into it from a little glass tube of which one end had been drawn out into a long and very thin capillary (so that by plunging it into the glycerine, the latter might be stirred as little as possible), while the other end was closed with a rubber cap. The photograph α on plate II shows three drops, successively forced out of the same little tube. They appear to change their shape rather slowly. The one at the right hand is the oldest; there diffusion has proceeded farther than with the other. In the drops, solutions of different specific gravity seem to form, part of the contents moving downward, and another part upward. We observe this more clearly still in β, where three drops at a later stage are shown. Inside all these drops the optical density is a minimum, also in the tiny filaments where diffusion has proceeded far. Everywhere the rule relating to case A is fully confirmed.

Some instances of case B are represented in γ, δ, ε. The vessel was filled with the salt-solution, and a few drops of the optically denser solution of glycerine were forced into it. Owing to the smaller viscosity of the medium, the drops change and move more quickly in this case. than in the former one; and because the photographing had to be delayed until a suitable stage of the diffusion process had been reached, these drops appear very irregularly lengthened out, as a rule. But the general character of the optical phenomenon is perfectly evident in this case too: a region of greater optical density appears dark toward the centre, and bright toward the edge of the source of light. All the thin filaments even, separating from the big drops in ε, show the same peculiarity.

And we see, that near the middle of the disk a condensation as well as a rarefaction can only *reduce* the brightness. If, therefore, we introduced into our vessel a great number of drops of greater or smaller optical density, so that the medium were honeycombed with density gradients, the central parts of the luminous field would show a much lesser average brightness, than if the medium were homogeneous. Incidentally, circumstances might co-operate to reproduce by refraction nearly the maximum brightness of the source, at certain places; those places would then highly surpass the average back-ground in brilliancy.

Places considerably brighter than the average photosphere are really observed now and then, even on the central parts of the disk. This fact has been cited by Fényi [1]) as an argument against the idea, that the light of prominences might be refracted photospheric light, because no optical system, no reflexion nor refraction, can ever make the intrinsic brightness of an object increase. Our above expla-

[1]) Memorie della Soc. d. Spettroscopisti italiani XXXVII p. 182 (1908).

nation, however, does not clash with this law; so the objection moved by FÉNYI is refuted.

With our liquids we can easily realize both cases A and B together and at the same time. We have but to fill the vessel with a mixture of equal parts of both solutions, and then to introduce one drop of each of the original solutions; we thus obtain a region with a minimum of optical density. The photograph ζ shows on the left a drop of glycerine, on the right a drop of salt solution in their opposite optical character.

On several grounds the existence of *vortices* in the solar atmosphere is considered probable. In the axis of a vortex the density is a minimum. The refraction in the region surrounding it, must be comparable with that in our extended drops. It is supposed that sun-spots are the seat of vortices with their axes more or less perpendicular to the photosphere [1]). Now let a spot be situated near the middle of the disk. Our line of sight will make only a small angle with the axis of the whirl; the light travels a long way through the non-homogeneous region, and the effect of ray-curving must be greater than in the case of a spherical rarefaction.

In order to realize similar conditions by experiment, we only need to send the light vertically through our liquids, because the drops extend chiefly in that direction.

The same diaphragm with ground-glass was fixed in a horizontal plane, and a vessel with bottom of plate-glass placed upon it. Two mirrors, one beneath and one above the vessel, and making angles of 45° with the vertical, enabled us to arrange the illuminating and the photographic apparatus in about the same manner as before.

Some results are to be found on Plate III. The photographs η and θ were obtained with salt drops in glycerine. Even on the middle of the luminous disk may now appear very dark spots whenever the line of sight makes but small angles with the long, almost cylindrical levels of equal density. Indeed, rays emerging in the direction of the line of sight from points near the axis of that rarefaction, suffered all of them such an intense incurvation, that they must have come from the dark surroundings of the source of light.

Just as in the former set of experiments the rarefaction, if situated far from the centre of the disk, shows always a bright rim toward that centre.

With glycerine drops in salt solution it was not so easy to obtain plain-shaped vertical filaments, on account of the greater mobility of

[1]) HALE, Contributions from the Mount Wilson Solar Observatory Nos. 26 and 30; Astroph. Journ. XXVIII, Sept. and Nov. 1908.

the liquid. Yet the photographs ι and $\varkappa$ suffice to show that, with these drops too, dark spots can be produced, which, in contrast with the former case, have a bright rim on the side opposite the centre.

Some observations were made with the vessel divided into two partitions by a glass plate. In λ the left part contained the optically thinner medium with a local condensation, the right part the denser medium with a rarefaction. Finally the image μ shows both cases in *one and the same* medium: on the left two salt-drops, on the right two glycerine drops are floating in a mixture of the two solutions. All these drops were lengthened in a direction nearly perpendicular to the plane of the image.

What is a sun-spot?

So far our results justify the suggestion, that the darkness of sun-spots and the distribution of brightness round about them might be mere consequences of refraction.

A difficulty arises. The typical sun-spot has a principal characteristic, which we do not observe as such in our imitations, namely: a *penumbra*, enclosing the *umbra*, from which, as a rule, it can be rather sharply distinguished. But this objection is easily removed.

Indeed, there is an essential difference between the arrangement of the gradients of optical density in a diffusing drop on the one hand, and round a vortex on the other hand. With the diffusing drop, the greatest gradients are to be found in the layer of quickest diffusion, that is, not far from the outside; whereas in the region of circulation, always surrounding a whirling mass of gas, *the gradients increase as we approach the vortex.*

It is not so easy, of course, to realize by experiment this latter case with its optical consequences; but that it must result in the appearance of an umbra and a penumbra, is clearly shown by the scheme fig. 3, plate I. Within the cylindrical space *abcd* the matter is supposed to be circulating about the vortex *W*. Rays directed towards the observer after emerging from the innermost parts of that region (the thin vortex-thread itself may be left out of regard) have suffered the greatest change of direction; they come from the space outside the photosphere, have little intensity, and produce the umbra. Parts of the spot, lying a little farther from the vortex, send us the light which left the photosphere tangentially: here we have the boundary between umbra and penumbra (in a certain sense: an inverted "image" of the solar horizon). Next follow the penumbra rays; first those having left the photosphere at great angles with the sun's radius, and therefore being the weaker ones; then, as we approach the outer limits of the region *abcd,* the rays that come gradually straighter from the source.

A disturbance of this "normal" arrangement of density gradients round a vortex may incidentally cause the photospheric light to follow a shorter path towards the observer, even through the central parts of the spot. The brilliant tongues and bridges, often observed in spots, find a natural explanation in this way.

Within a streaming mass of gas the velocity usually changes periodically (think of gusts of wind!); so there are shells of greater and of smaller density following each other alternately, and cutting the stream-lines at right angles. In the circulating matter round a vortex such shells must assume almost radial directions, but at the same time be slightly curved in a spiral shape. Refraction in an optical system thus constituted, brings about a distribution of brightness, known to us as the radial-filamentary structure of the penumbra [1]).

We do not want, in our spot theory, to make any special supposition as to the form of the region in which the density is a minimum. If it resembles a cylinder with its axis pointing towards us, the refraction effects will indeed be somewhat greater than if it were, for instance, spherical; but in the latter case too they may be strong enough and will bear the same principal character. Our explanation of the umbra and the penumbra rests on the only supposition, that in a certain region of the sun's atmosphere the density gradients are sufficiently great [2]), and gradually decrease from a central point outwards.

Anomalous dispersion in the region of a sun-spot.

So far we only dealt with the effects of refraction in general, without noticing the disparity of its values with the various waves of the spectrum, that is, the *dispersion.*

In general the refraction-constant of transparent media is positive; in the visible spectrum it increases with decreasing wave-length. Substances, however, showing absorption lines, may have refraction constants of such extreme variety of magnitude with the waves

[1]) The spiral-shaped flocculi visible on HALE's spectroheliograms with H_α (Astroph. Journ. XXVIII, Sept. 1908), and covering much greater regions, probably have a similar origin.

[2]) Astronomers who do not even hesitate to admit violent eruptions in sun-spots, and irregular velocities of many kilometres per second as a rule all over the sun's surface, will certainly not think the density gradients, required in our argument, unreasonably great.

belonging to the nearest vicinity of the absorption lines, that the above regular dispersion vanishes if compared with this anomalous dispersion. Waves lying on the *red*-facing side of absorption lines, and very near to them, we shall denote by R-light in this paper; neighbouring waves lying on their *violet*-facing side, we shall call V-light. With the R-light the refraction constant has rapidly increasing *positive* values as we approach the line; with the V-light it has rapidly increasing *negative* values as we approach the line.

The refracting power $n - 1$ of a gas is equal to the product $R\Delta$ of its refraction-constant into its density.

ARAGO and BIOT found that the refracting power of a mixture of gases equals the sum of the refracting powers of the constituents:

$$R_m \Delta_m = R_1 \Delta_1 + R_2 \Delta_2 + \textit{etc.}$$

As with most kinds of light all gases have a positive R, the refracting power $R_m \Delta_m$ of the mixture is in general positive. But with V-light $R_m \Delta_m$ may be negative, because that term of the sum, which bears upon the constituent producing the absorption line in question, may with V-light have a negative value so great, as to surpass the sum of the remaining, positive, terms. It is presupposed, of course, that the Δ of the said constituent is not too small, or in other words: the vibrating system, producing the line which we consider, should not be too scantily represented in the mixture.

Near lines of *principal* constituents the anomalous refraction predominates to such a degree, that the negative refracting power of the mixture with V-light is, in absolute magnitude, relatively little inferior to its positive refracting power with R-light.

What are we to conclude from these facts with regard to the spot-spectrum?

Let us first consider the case, that a region with a minimum of density is found just in front of the middle of the disk. Waves with which $R_m \Delta_m$ is positive, especially those belonging to the much refracted R-light, will in that region deviate conformably to the scheme of our drops of salt solution; the V-light, on the other hand, with which $R_m \Delta_m$ has great negative values, will in the same system of gradients deviate in the opposite way, that is, corresponding to the scheme of the glycerine drops. Both the R-light and the V-light are more weakened by dispersion than the rest of the spectrum: the Fraunhofer lines must in general be widened or winged in the spot-spectrum.

As the wings are caused by refraction, not by absorption, the spot-lines are not properly "widened absorption lines", but rather absorption lines, embedded in *dispersion bands* [1]).

Not all Fraunhofer lines are widened or strengthened in the spot-spectrum. The individual differences of behaviour I hope to refer to at a later date. For the present we have only to remember the fact, that the composition of the mixture of gases cannot be the same at all levels of the solar atmosphere. It therefore also depends on the level in which the local rarefaction occurs, which lines of the spot-spectrum will be enveloped in strong dispersion bands.

We shall now treat of the case that a rarefaction is projected on the solar disk at a certain distance from the centre.

The R-light must show a distribution of brightness reminding of that which we observed in our experiments with salt drops, that is: it is strengthened at the side of the spot, turned towards the centre of the disk, and very weak at the opposite side.

The V-light is curved the other way; the distribution will resemble that shown in our experiments with glycerine drops, that is: it is strengthened at the side, turned away from the centre, and very weak at the side, facing the centre of the disk.

These rules do not involve any special supposition as to the arrangement of the density gradients with respect to their magnitude. We may therefore make our idea of the manner in which the R-light and the V-light are distributed in an excentrically placed spot, more precise, by again introducing our previous assumption that in the spot-region the gradient decreases from the interior outwards. As a simplification we suppose that region to be nearly spherical.

Our figures 4 and 5 show the paths of the R-light and the V-light respectively. (Waves, not suffering anomalous refraction, will conform to the scheme fig. 4, as with them $R_m \Delta_m$ is positive, but the degree of refraction will be small; so they will produce a spot of which the umbra is smaller than the one represented in fig. 4). We see that with R-light the umbra is shifted towards the limb, whereas at the opposite side of the spot, in c, a bright place appears, because there emerges the light which left the photosphere perpendicularly. With the V-light, on the contrary, the umbra is shifted towards the centre, and the brightest light, emitted along the normal of the photosphere, emerges from p.

Two spectroheliograms of the same typical spot, simultaneously

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[1]) Proc. Roy. Amst. VII, p, 134—140; IX, p. 343—359.
Astrophysical Journal 21, p. 271—291 (1905) and 25, p. 95—115 (1907).

made with the R-light and the V-light of a suitable line [1]), should show the above difference very distinctly.

The spectroscope will reveal the following particulars.

Suppose the slit to be so placed in the sun's image, that it bisects the spot and coincides with a radius of the disk. In fig. 6 PC be a Fraunhofer line; P points to the periphery, C to the centre. The horizontal bands indicate the spectrum of the umbra and the penumbra as shown with light not undergoing anomalous refraction. With the R-light the umbra is greater and extends chiefly towards P (cf. fig. 4); so in the upper half of the spectrum the Fraunhofer line appears to be shifted to the red, and more markedly still, because at the same place in the spot the V-light attains its greatest brightness (cf. the point p in fig. 5). In the lower half of the spectrum R-light and V-light have changed parts [2]).

The widening of the line extends beyond the average penumbra because with R- and V-light the penumbra too is greater than with waves not subject to anomalous dispersion.

We conclude that in the spectrum of an excentrical spot — the slit bisecting that spot in the direction of the centre of the disk — the Fraunhofer lines must be more or less curved in the shape of the letter S, to a degree, depending on the intensity of the spot's distance from the centre of the disk. Whenever that distance is so

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1) Perhaps some iron line will serve the purpose better than one of the winged calcium or hydrogen lines, whose refraction effects might be confusingly great.

2) The distribution of the light in fig. 6 has been deduced from that in figures 4 and 5, in which process the shape of the dispersion curve, as given in fig. 8, is paid due attention to.

Indeed, one must imagine the whole spot of fig. 4 to appear smaller and smaller as the waves we are considering recede from the absorption line, because in fig. 8 the ordinates $(R_m\,\Delta_m)_R$ gradually decrease towards the red, until they reach the constant value $R_0\,\Delta_0$ (cf. p. 281). The distributions of the light along a cut PC through fig. 4, such as they would successively appear with increasing wave-lengths, were plotted side by side in fig. 6, going from the absorption line to the red.

On the violet side of the line one has to proceed in the same way. There the negative ordinates of fig. 8 decrease as we recede from the line, and the distribution of the light prevailing along a cut PC through fig. 5, must be transferred to fig. 6 on a smaller and smaller scale. But in the point c' of fig. 8 we have $(R_m\,\Delta_m)_V = 0$; light of that wave-length suffers no refraction at all in the solar atmosphere, so that the spot-spectrum is here interrupted. Next, $(R_m\,\Delta_m)_V$ attains positive values, increasing up to $R_0\,\Delta_0$; the distribution of the light has again to be taken from fig. 4.

So the spot-lines are not only inclined, but also asymmetric, a feature which especially the weaker lines will show, provided that the dispersion of the spectral apparatus be sufficiently high.

small, that there is no sufficient asymmetry in the supply of light, the inclination of the lines becomes imperceptible.

With any other direction of the slit the effect must be less; t vanishes when the slit bisects the spot in a direction at right angles to a line joining the spot and the centre.

Is it necessary to admit radial movement in sun-spots?

Bulletin N°. XV of the Kodaikánal Observatory (Febr. 1909) contains a remarkable communication by J. EVERSHED, entitled: "Radial movement in sunspots". The new facts there described chime perfectly and in every detail with the above necessary consequences of refraction. In the spectra of all the spots examined Mr. EVERSHED found the lines displaced according to the following law. Wherever a spot be situated on the solar disk — provided that the distance from the centre surpasses 10° — the majority of the Fraunhofer lines of its spectrum are slightly inclined when the slit bisects the spot in the direction toward the centre of the disk. The inclination is less with other directions of the slit, and disappears when the slit is at right angles to the sun's radius. The displacement of the lines is always to the red on the side of the spot, turned towards the limb, and to the violet on the side facing the centre; it differs in magnitude with the individual lines [1]).

To explain these phenomena Mr. EVERSHED invokes DOPPLER's principle. He attributes the displacements to a radial movement outwards from the spot-centre. The motion must be essentially horizontal, or parallel to the sun's surface; the velocity seems to increase, from the centre of the spot outwards, yet at the limits of the penumbra the motion apparently ceases abruptly. The lines of the true umbral spectrum seem usually to be almost entirely unaffected by motion in the line of sight. So there is not a kind of spring in the umbra, and we are puzzled with the question, whence the matter comes, which is permanently spreading out in the spot, and where it accumulates. Moreover, the maximum velocities indicated by the

[1]) H_β was not inclined We presume that the anomalous refraction produced by the hydrogen of the solar atmosphere is *too considerable* to become apparent in the same way as the refraction caused by other elements. Even in the average solar spectrum the dispersion band of H_β is more than one Ångström unit wide; in the spotspectrum it may perhaps extend so much farther, that one is inclined to look upon it as not belonging to the line, and, therefore, to consider the line as weakened. Now, the narrow central line is the real *absorption* line H_β, which of course cannot be displaced or curved by refraction.

displacements of different lines range from 0 to more than 2 kilometers per second, so that the elements would move independently. And Mr. EVERSHED himself remarks, that the hypothesis of a radial movement in spots seems entirely out of harmony with the conclusions arrived at by Prof. HALE in his researches on vortices and magnetic fields in sun-spots.

To my mind, the difficulties involved in Mr. EVERSHED's explanation of the important facts which he has discovered are insuperable. Motion in the line of sight cannot be the cause of those systematic displacements. Neither can they be accounted for by pressure or by the influence of a magnetic field, without introducing very improbable hypotheses *ad hoc*. On the other hand I could not find any serious difficulty in describing the newly-discovered phenomena as mere consequences of the anomalous refraction of photospheric light in local rarefactions of the solar atmosphere.

On the origin of the Fraunhofer lines.

We considered a sun-spot as a region in which the density gradient regularly decreases in all directions from the centre outwards, thus preserving the same sign unto the outer limit of the penumbra.

Density gradients of the same order of magnitude are supposed to occur just as well outside the spots, at many places throughout the solar atmosphere, but there they are not arranged by the systematizing influence of an important vortex, and often change their sign.

Now if the widening of the Fraunhofer lines in the spot-spectrum must be ascribed to anomalous dispersion in extensive regions containing a deep "depression", why should not the width of the lines in the ordinary solar spectrum also be caused for a considerable part by dispersion in minor rarefactions and condensations?

At first sight the evidence seems unfavourable to this view. For one might contend that, if the R-light and the V-light were not really *absorbed* in the solar atmosphere, but only dispersed, such waves must leave the sun after all, be it at points very distant from those where they emerged from the photosphere, and could not, therefore, be wanting in the *average* sun-light.

But this argument is incorrect.

To understand this, imagine the whole solar atmosphere divided by surfaces into alveoles or cells in such way, that each cell encloses either a maximum or a minimum of density. The shape of the cells will vary to the extreme.

Let us first consider a nearly spherical cell enclosing a *minimum* (fig 7). All the light which, coming from the photosphere SS', enters this region in a direction, making an angle φ with the normal to the photosphere, will leave the cell as a diverging beam. The spreading is wider in proportion as the refraction constant R_m for the kind of light considered is greater. (If R_m is negative, the rays will first converge, but afterwards diverge just as well).

With small values of φ and moderate refraction, all the incident rays will leave the cell in such directions, that they continue to move away from the photosphere. But with larger values of φ as well as of R_m there is increasing chance, that some of the dispersed rays are directed back to the photosphere and thus prevented from leaving the sun.

The total quantity of light entering our cell is found by integrating round the normal, and with φ between the limits 0 and $\frac{\pi}{2}$. (It is true that into our cell some light will enter, which comes from higher levels, where it has been refracted downward by other cells, but that contribution is small in comparison with the supply from beneath). All this light would be emitted by the celestial body if there were no incurvation of rays; but now a part returns to the photosphere. That part is greater in proportion as R_m has greater (positive or negative) values.

The cells are not spherical indeed, but it is clear that if other shapes are considered, our result must on the average continue to hold. And a cell enclosing a *maximum* of density, makes the rays first converge, then diverge if R_m is positive, and makes them always diverge if R_m is negative.

So *all* the inequalities of the density co-operate to prevent a certain part of the light of the photosphere from passing through the solar atmosphere. [1])

In the solar spectrum the waves, which belong to the nearest vicinity of the absorption lines, appear with less intensity than the other waves, not because they are absorbed in the solar atmosphere, but because they are partly directed back to the interior. The Fraunhofer lines are absorption lines, enveloped in dispersion bands.

Asymmetry of the Fraunhofer lines.

From our modified conception of the solar spectrum — which only supplements KIRCHHOFF's interpretation — it follows that all

[1]) The same refraction effect must also cause the brightness of the disk to decrease from the centre to the limb, even if perhaps the cosinus-law holds for the radiation of the photosphere, and independent of a general absorption which the solar atmosphere might exert. (cf. the footnote on p. 268).

Fraunhofer lines must show certain systematic distinctions as compared with the character of pure absorption lines.

Dispersion bands, produced by the solar atmosphere, must be asymmetrical, the narrower ones to a higher degree than the wider ones.

Indeed, we may represent the refracting power of that atmosphere for each kind of R-light appertaining to a given line, by the expression:

$$(R_m \Delta_m)_R = (R_1 \Delta_1)_R + (R_0 \Delta_0)_R$$

in which the term $R_1 \Delta_1$ relates to the constituent of the atmosphere producing the line in question, and $R_0 \Delta_0$ means the refracting power of the mixture of the remaining constituents. Both terms are positive.

In a similar expression, concerning the V-light of the same line:

$$(R_m \Delta_m)_V = (R_1 \Delta_1)_V + (R_0 \Delta_0)_V ,$$

the term $(R_0 \Delta_0)_V$ will not differ to any appreciable degree from $(R_0 \Delta_0)_R$; but now R_1 is negative. At equal distances on either side of the absorption line, R_1 has (according to the law of anomalous dispersion) nearly equal values of opposite sign. If, therefore, we select on the violet side of the line a wavelength, matching the first-chosen R-light symmetrically, we may write:

$$(R_m \Delta_m)_V = -(R_1 \Delta_1)_R + (R_0 \Delta_0)_R ,$$

so that, with such pairs of wave-lengths, the relation holds:

$$(R_m \Delta_m)_R + (R_m \Delta_m)_V = 2 R_0 \Delta_0 = const.$$

Suppose we approach the line from both sides in a symmetrical way, then $(R_m \Delta_m)_R$ and $(R_m \Delta_m)_V$ begin with being positive; one increases, the other decreases, and when $(R_m \Delta_m)_R$ has reached the value $2 R_0 \Delta_0$, $(R_m \Delta_m)_V$ passes zero, and is going to take increasing negative values. But in *absolute magnitude* $(R_m \Delta_m)_V$ will always be inferior to the corresponding $(R_m \Delta_m)_R$; the difference grows from 0 to $2 R_0 \Delta_0$, and then remains constant when we approach nearer to the absorption line.

Figure 8 serves to elucidate this. The ordinates a and a', b and b' etc. represent values of $R_m \Delta_m$, bearing upon waves that are symmetrically situated with respect to the absorption line. The ordinates of the dotted line have the nearly constant value $R_0 \Delta_0$.

The degree to which the light is dispersed by refraction in the solar gases, is determined by the *absolute magnitude* of $R_m \Delta_m$; so the average effect must be greater on the red side of an absorption line than on the violet side. The asymmetry of the dispersion band must manifest as a displacement of the Fraunhofer line towards the red. If however the terms $\pm R_1 \Delta_1$ are highly predominating in a rather wide band of the spectrum, in other words, if the vibrating systems which give rise to our line constitute an important part of the solar atmosphere, the asymmetry, and with it the displacement, become imperceptible.

A displacement of the majority of the Fraunhofer lines towards the greater wave-lengths, amounting to a few thousandth parts of an Ångström unit, was discovered by JEWELL as early as 1896. But there were numerous exceptions: lines showing no displacement, or a displacement towards the violet (with respect to their positions in the emission spectrum produced in the laboratory).

Recently M. M. FABRY and BUISSON [1]) applied their fine, extremely accurate interferential method in comparing iron lines of the arc-spectrum with those of the solar spectrum. Only narrow lines could be studied in that way. Their results confirmed those obtained by JEWELL: in general displacement to the red, but many exceptions. The latter, however, appeared to bear exclusively upon lines which under ordinary circumstances are not very sharp in the arc-spectrum, and are widened asymmetrically when the current is increased. With such lines the localisation in the emission spectrum had perhaps not been so accurate as could be desired. FABRY and BUISSON succeeded [2]) in making these dubious lines perfectly sharp, by producing the iron-arc in vacuo. On comparing the solar spectrum with the arc-spectrum thus obtained, they found, that the exceptions had disappeared: all the lines examined were shifted to the red in the Fraunhofer spectrum. The displacements ranged from 0,005 to 0,010 Ångstr. units with lines whose width varied between 0,07 and 0,16 units (intensity 1 to 8 according to ROWLAND's scale).

At the beginning of their interesting communications FABRY and BUISSON remark: "Le déplacement des raies permet (donc) de mesurer les variations de pression. En comparant les raies du spectre solaire avec les raies correspondantes de l'arc à la pression atmosphérique, on a un moyen d'évaluer la pression de la couche renversante, si toutefois aucun autre phénomène n'intervient." Supposing that there were no other disturbing phenomena except those which they had excluded in their experiments, they calculate that the average pressure in the reversing layer must be from 5 to 6 atmospheres.

We hold the opinion that this valuation is certainly too high. Indeed, the observed displacements cannot have been exclusively produced by pressure, because refraction is sure to bring about line-shifts in the same direction. And if perhaps future research might induce one to think it probable, that at the same level of the sun the pressure

1) FABRY et BUISSON, Comptes rendus, 15 mars et 29 mars 1909.

2) FABRY et BUISSON, Comptes rendus, 10 mai 1909.

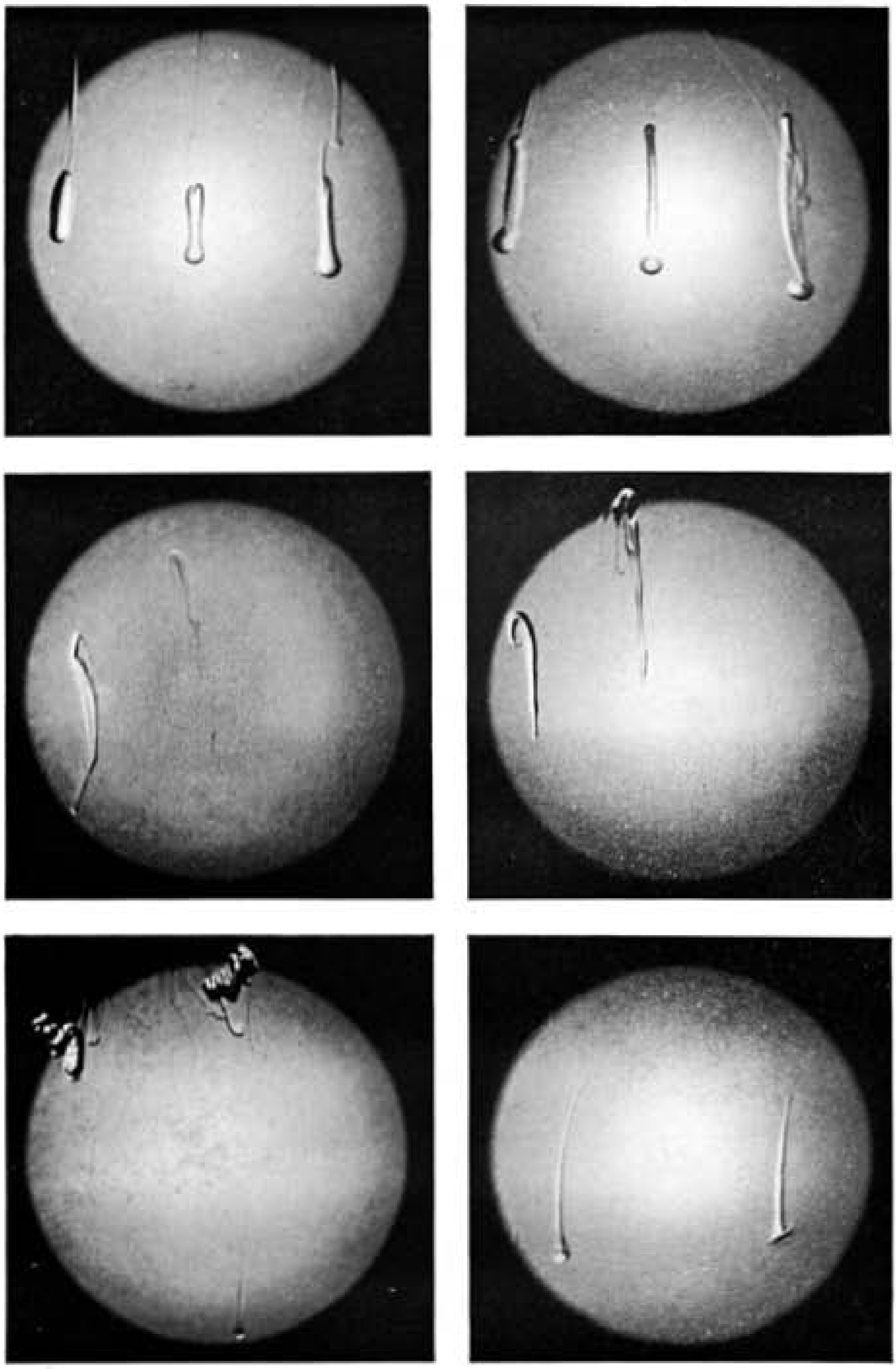
W. H. JULIUS. "Regular consequences of irregular refraction in the sun."

Plate II.

α

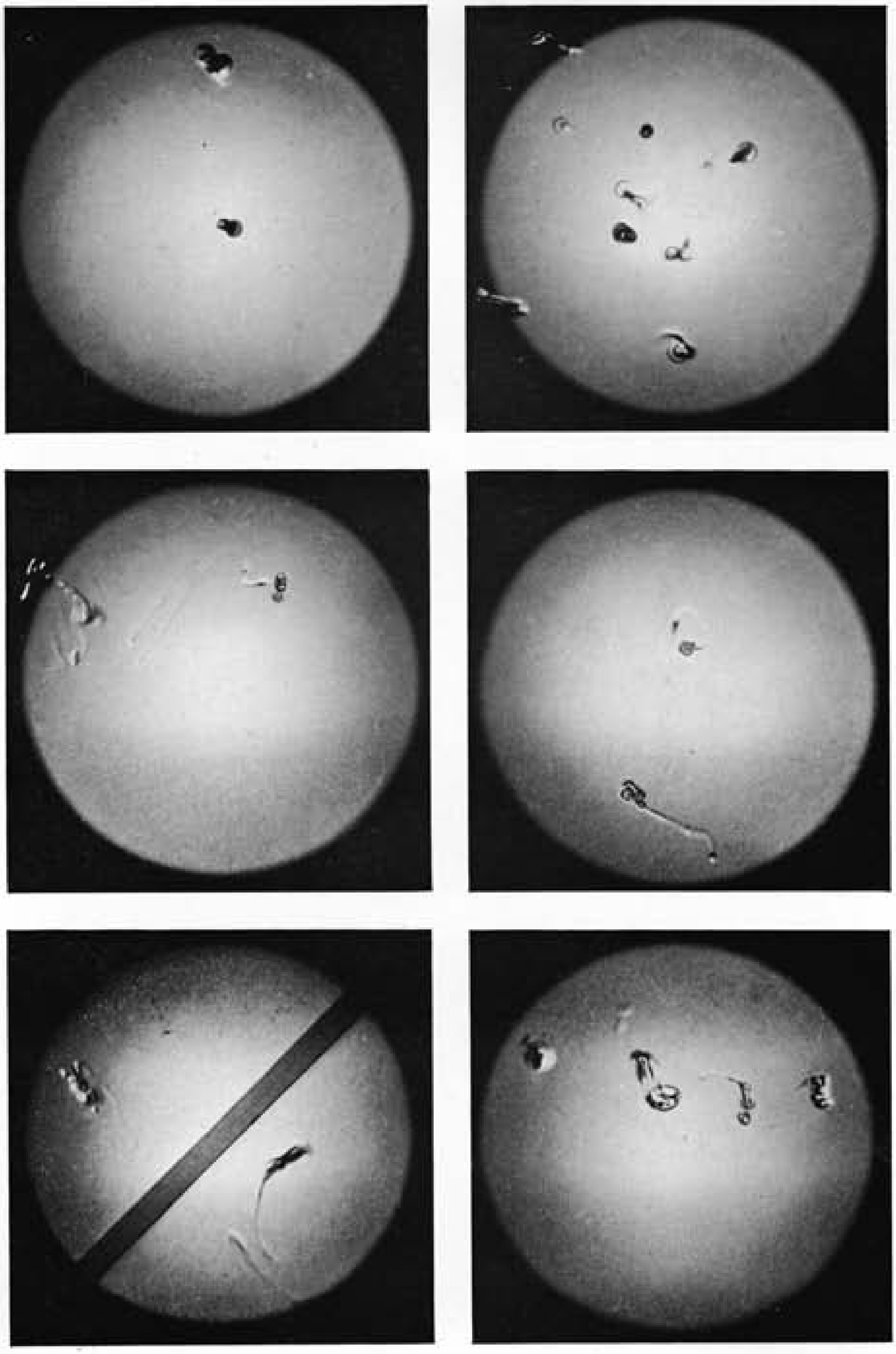
γ

ε



W. H. JULIUS. "Regular consequences of irregular refraction in the sun."

Plate III.



η θ

ι $\varkappa$

λ μ

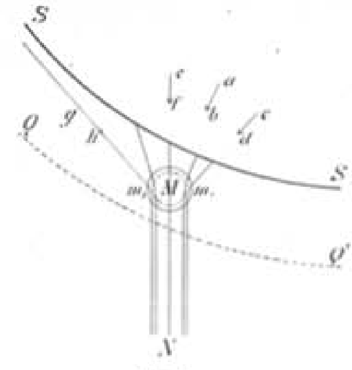


Fig 1.

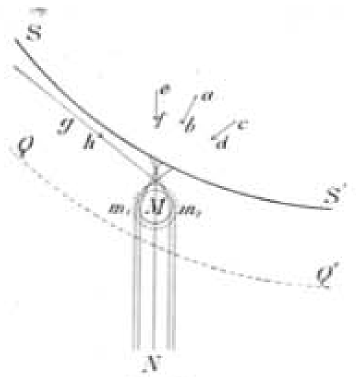


Fig. 2.

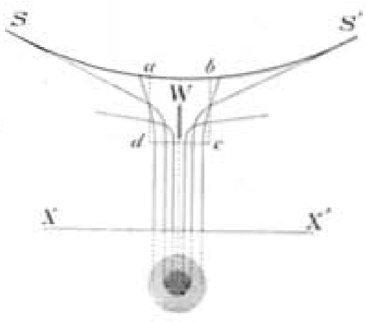


Fig. 3.

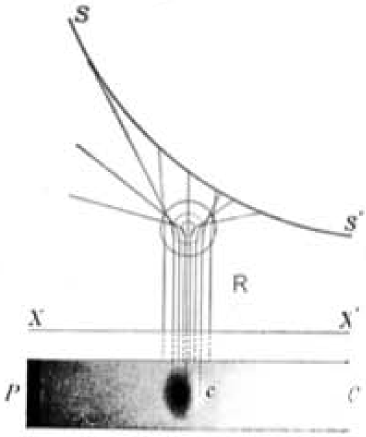


Fig. 4.

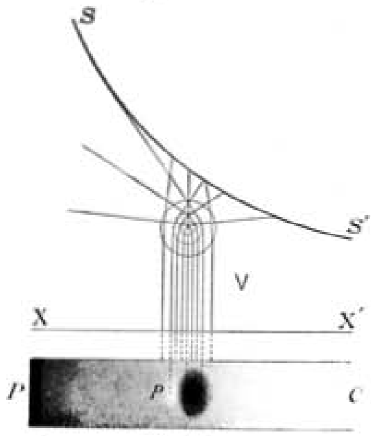


Fig. 5

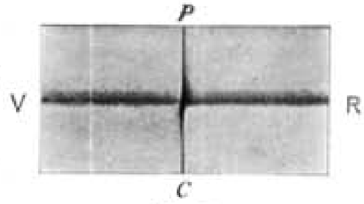


Fig. 6.

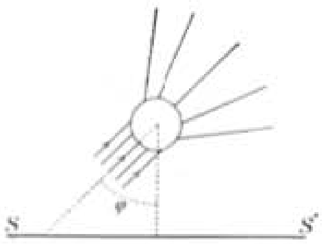


Fig. 7.

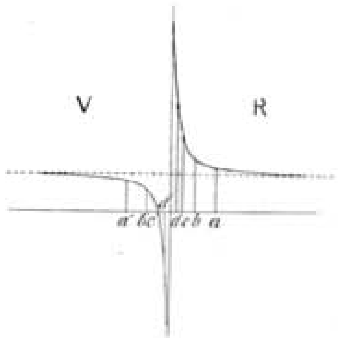


Fig. 8.

is *very* much smaller than 5 or 6 atmospheres, there will be no incompatibility with FABRY and BUISSON's observational results, because anomalous dispersion can be made responsible for the *whole* effect.

Similar considerations apply to another general result of recent observations, viz. to certain systematic differences existing between the spectrum of the centre and that of the limb of the disk.

BUISSON and FABRY resume the facts as follows[1]):

1. Il y a un changement d'aspect pour certaines raies. Pour les fortes raies, la pénombre est affaiblie dans le spectre du bord. Parmi les autres raies, quelques-unes sont renforcées ou affaiblies sur les bords du disque, et le changement est en général de même sens que dans le spectre des taches[2]).

2. HALM a annoncé[3]) que certaines raies subissent, du centre aux bords, un léger accroissement de longueur d'onde; ses mesures ont été faites sur deux raies rouges du fer, en comparant leurs positions à celles de deux raies telluriques voisines. Il a trouvé un déplacement de 0,012 angström.

Using their interferential method BUISSON and FABRY examined into 14 lines of various metals (intensities 2 to 6 on ROWLAND's scale), and found HALM's result confirmed: a displacement to the red, varying between 0,004 and 0,006 Ångstrom units, when passing from the centre to the limb. (Two vanadium lines were not displaced). Moreover, those same lines appeared to be about 0,010 Ångstrom units wider at the limb than at the centre of the disk. So we may take it as if the widening affects chiefly the red-facing side of the lines.

If one wishes to interpret this phenomenon too by means of the pressure effect — as the discoverers did — one must admit that deeper layers, in which the pressure is higher, contribute relatively more to the formation of the absorption lines near the limb than near the centre of the solar disk.

We will not dwell on various difficulties, encountered in developing this idea; probably it will be possible to remove them by introducing additional hypotheses concerning the thickness of the layers, or the temperature and other physical conditions of the absorbing vapours.

At all events it is unnecessary to ascribe the above differences between the spectra of the central and the marginal parts of the disk entirely to pressure; for anomalous refraction — which undoubtedly comes into play — acts exactly in such a way, that in the

1) BUISSON et FABRY Comptes rendus, 28 juin 1909.
2) HALE and ADAMS. Astroph. Journ. **25**, June 1907.
3) HALM, Astronomische Nachrichten, nos. 4146—47, 1907.

spectrum of the limb a widening of narrow lines, especially on their red side, is to be expected.

Indeed, rays coming from the limb have, as a rule, accomplished a longer distance through the solar gases than rays coming from the centre, and, therefore, were more subject to loss of intensity by the process of incurvation towards the photosphere. The amount of the irregular ray-curving depends on the absolute magnitude of $R_m \Delta_m$, which (near the weaker lines of the solar spectrum) is sensibly greater with R-light than with V-light. So the lines must chiefly widen at their red-facing side, in proportion as the opportunity for losing light increases.

That the character of the limb-spectrum resembles that of the spot-spectrum in many respects, is immediately explained by the refraction theory. Indeed, the light which we receive from the inner zones of the penumbra, has followed paths, along which the conditions of limb-rays prevail, (cf. fig. 3).

On the other hand, there are numerous peculiarities in the behaviour of various Fraunhofer lines, which we cannot so easily explain by simply applying the laws of refraction — either because entirely different processes are involved, or perhaps because the consequences of refraction have to be more deeply scrutinized. (We remind of the weakening of the wings of the stronger lines in the limb-spectrum; of the weakening of several lines in the spot-spectrum; of the different way in which the hydrogen lines behave in the spectra of the limb and the spots, etc.). All this requires an ample study of details, in which it is necessary to dispose of an extensive collection of observational data.

Finally I wish to call attention to an inference deduced from our conception of the Fraunhofer spectrum, which, to my knowledge, is not yet supported by any direct observation.

Among the various kinds of V-light of each line, one kind must exist, for which $R_m \Delta_m = 0$ (at c' in fig. 8). Rays of this and of neighbouring wave-lengths suffer less refraction than rays, belonging to blank parts of the spectrum; so they must produce strips of greater brightness (pseudo-emission lines) in the spectrum of the centre of the disk. With strong Fraunhofer lines the point c' lies far away, on a part of the dispersion curve so slightly inclined, that the bright band must be vague and inappreciable; but with narrower lines the bright companion will also be narrow, and relatively more conspicuous. Its distance from the absorption line is always smaller than the width of the Fraunhofer line. By applying the extremely sensible method of Fabry and Buisson the bright lines may perhaps be detected.

(October 28, 1909).