SOLAR PHENOMENA, CONSIDERED IN CONNECTION WITH ANOMALOUS DISPERSION OF LIGHT.[1]

By W. H. JULIUS.

THE rule that the propagation of light is, in all directions, rectilinear, holds only for quite homogeneous media. If various considerations lead us to assume that the solar rays on their course penetrate media of unequal density, or of different composition, the rays must be curved, and the supposition that the observed light is emitted by objects situated in the direction of vision becomes untenable.

Now, though no one doubts the unequal distribution of matter in and near the Sun, yet in theories concerning this celestial body hardly any attention has been paid to refraction. The study of atmospheric refraction had, long since, made us acquainted with the laws of curved rays[2] but the first important attempt to investigate the influence which refraction in the Sun itself must have had on the course of the rays which reach our eye, and consequently on the optical image we get of it, was made by Dr. A. Schmidt. His paper "Die Strahlenbrechung auf der Sonne; ein geometrischer Beitrag zur Sonnenphysik"[3] leads to very remarkable results, and at any rate urges the necessity of submitting the existing theories of the Sun to a severe criticism from this point of view.

If it is taken for granted that refraction in the solar atmosphere must be taken into account we must also pay attention to those special cases in which extraordinary values — great or small — of the refractive index occur; in other words, the phenomenon of anomalous dispersion must be reckoned with.

[1] *Proceedings of the Royal Academy of Sciences*, Amsterdam.

[2] The literature on this subject may be found in a dissertation by O. Wiener, *Wied. Ann.*, 49, 105-149, 1893.

[3] Stuttgart, Verlag von J. B. Metzler, 1891.

It is my purpose to show that many peculiarities, which have been observed at the limb of the Sun and in the spots, may easily be considered as caused by anomalous dispersion.

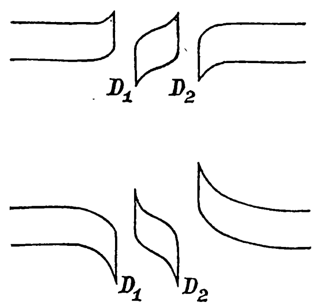
It is not difficult to obtain the experimental evidence that the index of refraction of sodium vapor for light differing but slightly in wave-length from that for the D lines, is very different from the index for the other rays of the spectrum.

H. Becquerel[1] used for the study of the phenomenon Kundt's method of crossed prisms, in a slightly modified manner. The image of the crater of an arc-light was projected on a horizontal slit, placed in the focus of a collimator-lens. The parallel beam next passed through a sodium flame, which Becquerel had succeeded in giving the form of a prism with horizontal refracting edge, and was then, through a telescope lens, focused into an image of the horizontal slit, falling exactly on the vertical slit of a spectroscope of rather great dispersion. As long as the sodium flame was absent, a continuous spectrum was seen in the spectroscope, the height of which naturally depended on the width of the horizontal slit. When the flame was introduced in its proper place, and good care was taken to limit the parallel beam by means of an easily adjusted diaphragm, in such a manner that only such light could penetrate into the telescope lens as had passed a properly prismatical part of the flame, the spectrum clearly exhibited the anomalous dispersion. On either side of the two dark sodium lines the originally horizontal spectrum-band was boldly curved, so that for rays with wave-lengths slightly larger than λ_{D_1} or λ_{D_2}, the sodium vapor appeared to possess an index of refraction rapidly increasing in the neighborhood of an absorption line; whereas for rays of wave-lengths slightly smaller than λ_{D_1} or λ_{D_2}, the index of refraction rapidly decreased when approaching the absorption lines. The amount of the anomalous dispersion near D_2 exceeded that near D_1.

In repeating this experiment I obtained materially the same results. Moreover, I noticed a peculiarity in the phenomenon, not mentioned by Becquerel, and not exhibited in the diagrams

[1] *C. R.*, **127**, 399; and **128**, 145.

accompanying his paper. Becquerel states that when he introduced a flame, rich in sodium, the lines D_1 and D_2 appeared as broad, dark bands, and that on either side of both bands the spectrum was curved. According to his diagrams these displacements only refer to light outside the bands; the rays inside this region, in the more immediate neighborhood of the D lines, are totally wanting. Fig. 1 refers to a prismatic part of the flame, edge upwards; Fig. 2, to a prismatic part, edge downwards. Both cases represent the image as seen in a telescope, and are thus reversed.



FIGS. 1 AND 2.

I myself, however, have observed the phenomenon in the form of Fig. 3. The dotted lines indicate the places of D_1 and D_2. When the electric light is intercepted by means of a screen introduced between the flame and the horizontal slit, the D lines appear in those places as two faintly luminous, sharply defined slit-images. The light is faint because the flame is placed at a distance of more than 70 cm from the vertical slit, and its radiation is all but intercepted by the adjustable diaphragm, which allows only a beam of a cross-section of about 0.2 cm^2, to enter the telescope lens.

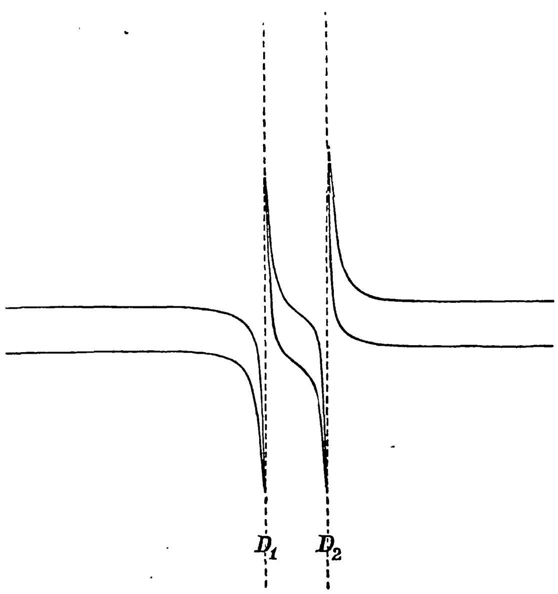


FIG. 3.

When next the arc light is allowed to cross the flame, the spectrum of Fig. 3 appears with such intensity that the bright sodium lines are undistinguishable in the center of the dark bands. In the upper and lower parts of the field of vision, however, they can yet be seen as continuations of the four bright arrows of light which are, as it were, flashed forth from the horizontal spectrum into the dark.

By repeatedly intercepting and readmitting the light of the main source, I have actually convinced myself that the intense arrow-light, with the dispersion used, gradually passes into the faint light of the emission-lines, both with respect to intensity and place in the spectrum. A flat Rowland grating with 47,000 lines was used in the spectroscope; one spectrum of the first order being extremely brilliant. The crosswires of a micrometer eyepiece (65 divisions of which correspond to the distance of the D lines in the first diffraction spectrum) were repeatedly adjusted as close as possible to the extreme part that was yet distinctly visible of such an arrow, the sodium lines of the flame being all but invisible. I next removed the diaphragm near the flame, intercepted the main light so that the sodium lines now became clearly visible, and took a number of the readings of the emission line. The mean readings of two series of observations did not mutually differ by one division; the arrow, therefore, approached the D line to within 0.01 $\mu\mu$. From the data furnished by Becquerel[1] it can be inferred that the distance between the D lines and the most deflected parts of the arrows upon which, in his experiments, the crosswires could still be adjusted, was on an average greater than 0.1 $\mu\mu$.

I am not quite sure how this difference in the results must be accounted for; perhaps Becquerel's flame contained more sodium than mine; anyhow so much sodium is not wanted to produce strong anomalous dispersion.

The following experiment convinced me how narrow was in reality the absorption-region of each of the sodium lines. An additional lens of 20 cm focal distance was placed between the telescope lens and the vertical slit, in such a manner that on this slit was thrown the image of the prismatic part of the sodium flame, and not that of the horizontal slit, as before. In this image, therefore, all rays that had passed the flame and had been refracted in different directions, must be found reunited.

[1] *C. R.*, **128**, 146.

The absorption lines were now actually very narrow, the emission lines in some places all but covering them.

The additional lens being removed, the light-arrows forthwith reappeared above and below the rather broad dark bands in the curved spectrum.

It appears, therefore, from our observations that in spite of the considerable width of the dark bands in the main spectrum, the corresponding light is but very slightly absorbed by the sodium lines. The flame has allowed every kind of light to pass, even that of which the wave-length differed ever so little from that of the D lines; but it has caused these rays to be deflected from the straight line much more forcibly than the other parts of the spectrum lying further removed from the absorption lines.

Here, then, we have a case where the absorption spectrum of a vapor exhibits broad bands not deserving the name of absorption bands. The special manner in which the experiment was made enabled us to see what had become of the light that had disappeared around the sodium lines; but very likely the broad bands would have been attributed entirely to absorption if somehow this abnormally refracted light had fallen outside the field of vision of the spectroscope. In studying the absorption spectra of gases and vapors, we should be careful to see—which is not always done—that the absorbing layer shall have equal density in all its parts and shall not act anywhere as a prism. It would be worth while investigating in how far the anomalous dispersion can have influenced cases in which broadening or reversal of absorption lines have been observed.

In my arrangement the absorption lines were narrow, if the main light had passed through a nearly homogeneous and *non-prismatic* part of the flame.

The experiment, as described above, offers no opportunity for obtaining reliable values of the refractive indices. A better method to arrive at more reliable results is now being investigated; for the present all we can say is that the deviation of rays whose wave-length is very near λ_{D_1}, or λ_{D_2} is at least six or eight times greater than that which the remoter parts of the spectrum were subject to. Becquerel says that the index for waves greater than λD_1 and λD_2 may attain 1.0009; for waves on the other side of the absorption line the index falls considerably below unity. The line D_2 produces in a much higher degree than D_1 refractive indices smaller than unity;[1] the very high indices are represented in pretty much the same degree near D_1 and D_2.

From all this we infer:

1. Where light emitted by a source that yields a continuous spectrum traverses a space in which sodium vapor is unequally distributed, the rays in the neighborhood of the D lines will be much further deflected from their course than any others. Of all things this holds good of those rays whose wave-length differs so little from λD_1 and λD_2 that they can hardly be distinguished from sodium light. A pretty strong light, therefore, misleadingly resembling sodium light, but in reality owing its existence to other sources, may seem to proceed from a faintly luminous sodium vapor, in a direction deviating from that of the incident light.

2. A spectroscopic examination of the light that has traversed, in a fairly rectilinear direction, the space filled with sodium vapor, shows, in the places where the D lines are to be found, broad dark bands, owing to the fact that the light of these places in the spectrum has deviated sideways from its course and has not reached the slit of the spectroscope.

The former of these inferences we will now apply to certain phenomena in the neighborhood of the disk of the Sun; the latter to some peculiarities of the Sun-spots.

Let the arc ZZ' (Fig. 4) represent a part of the disk of the Sun, the observer being stationed far off in the direction of O. This ZZ' may be taken to be either the limit of the photosphere, or the critical sphere which, in A. Schmidt's theory of the Sun, plays such an important part. In either case, a ray emitted from

[1] In Fig. 3, page 187, the upper arrow near D_2 is defective and rather short compared with that near D_1.

any point *A* on the surface, at an angle of nearly 90°, will reach the point *O* along a path the curvature of which diminishes regularly, if we assume that the density of the Sun's atmosphere in a direction normal to the surface decreases continuously.

A ray emitted from *B* under the same circumstances will proceed along *BO'* and does not, therefore, reach *O;* the observer at *O* will see *A* lying just within the margin of the disk of the Sun; light proceeding from *B* is invisible to his eye. Slight irregularities of density in the atmosphere on the path *AO* will

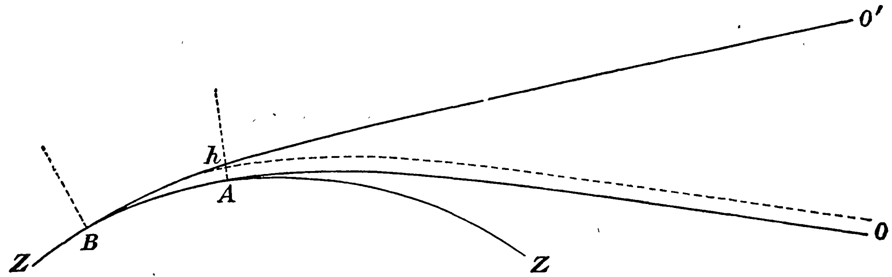


FIG. 4.

indeed deflect the course of the rays, but only slightly if the gases have a normal index of refraction. The irregularities show themselves as shallow elevations and depressions in the edge of the Sun's disk. In the same manner, rays like *BO'* do not materially deviate from the course which they would have to follow in a perfectly calm atmosphere of continuously decreasing density.

Let us now suppose unequally distributed sodium vapor to be present near *A* above the limit *ZZ'* (the photosphere). We suppose this vapor to be hardly luminous, if at all. The greater part of the beam of white light *BO'* is only slightly irregularly refracted in it, just as in the other gases to be found there; but those rays whose wave-length differs but slightly from λD_1 or λD_2 are much more deflected, and they may even follow the course indicated by the dotted line *BhO*. Then from *O*, at a small distance *Ah* above *A*, light may be seen proceeding from *B*—a source of light with a continuous spectrum—closely resembling sodium light. A spectroscopic examination of this light, however, will show that it differs more or less from that of the D lines.

It might be thought that only rays with an abnormally high refractive index, *i. e.*, with wave-lengths rather greater than λ_{D_1} or λ_{D_2}, can reach the observer along the path *BhO*. Such, however, is not the case; for if above *A* there were a layer comparable to a prism with the refracting edge perpendicular to the plane of the cut and with base turned upwards, rays with an index smaller than unity must be able to traverse the path *BhO*.

Accordingly in the spectrum of the light that appears outside the Sun's disk we can expect to find rays which are situated on either side of the D lines; perhaps the probability is a little greater for the light on the red side of the absorption lines, because from *A* to *h* the density is more likely to decrease than otherwise.

It is further clear that very near the limb there is the greatest probability of also seeing light that differs relatively much in wave-length from the sodium light; for there a less degree of abnormality of index suffices to deflect rays in the direction of *O*. On the other hand, far above *A*, we can, as a rule, discern only such light as is hardly to be distinguished from D light.

These actually prove to be the principal characteristics of the chromosphere lines. Generally they have a broad base and are arrow-headed. Compare the description and the diagrams to be found in Lockyer's *Chemistry of the Sun*, pp. 109 and 111.

Their typical form appears very strikingly in the hydrogen lines of the chromosphere.

There is no reason to assume that the above considerations, with regard to sodium vapor, do not hold good as well for other gases and vapors. With some of these the anomalous dispersion has been proved already;[1] with others we have been less successful, but the dispersion theories point to its existence in a greater or less degree in all substances.

The characteristic form of the chromosphere lines might, of course, also be accounted for, as is generally done, by the

[1] WINKELMANN, *Wied. Ann.*, **32**, 439.

strongly radiating luminous gases and metallic vapors which are thought to be present in the chromosphere, and of which the density near the photosphere must then be taken to be very considerable and to be rapidly decreasing at greater distances. The observed light would then be emitted by those glowing vapors.

Our view of the origin of the chromosphere light does not by any means preclude the possibility of this light owing its existence, partly at least, to self-radiation of incandescent gas; what we have shown is that it may also be refracted photosphere light. Further investigation of the various phenomena of the Sun must decide which explanation goes farthest in considering the whole subject.

Sometimes the chromosphere lines appear under very singular forms, with broadenings, ramifications, plumes, detached parts, etc.[1] Thus far this has been accounted for only on the principle of Doppler, viz., by assuming that the radiating gases move towards, or away from us with tremendous velocity—even as much as 200 km per second and more. Astronomers are all agreed that this explanation is open to many objections, of which we need not remind the reader here.

Beside Doppler's principle, however, we find in the anomalous dispersion another, according to which a gas has the power to originate, under certain circumstances, light differing in wave-length from the characteristic rays of that substance.

Let us suppose, for example, that at some distance above the Sun's limb there is a quantity of hydrogen, with great varieties of density in some of its parts. It will emit not only its own characteristic light, but will, here and there, also deflect earthwards the photosphere light of adjacent wave-lengths. This will, of course, manifest itself in excrescences or ramifications of the hydrogen lines, or as isolated light patches in their neighborhood.

This phenomenon may be expected especially when the slit is adjusted for the examination of prominences where violent

[1] *Cf.* LOCKYER, *loc. cit.*, p. 120.

disturbances take place and where, consequently, considerable differences of density occur.

Though the present explanation of these irregularities in the spectrum is based, like the other one, on the hypothesis that violent disturbances in the solar atmosphere go hand in hand with them, yet the tremendous velocities, required when applying Doppler's principle, do by no means follow from it.

A portion, therefore, of all the light that reaches us from chromosphere and prominences *may* be due to self-luminosity of the gases to be found there; but another, and to all likelihood a very considerable portion is refracted photosphere light reaching us in a manner that reminds us of Töpler's well-known "Schlierenmethode." But there is this difference, that in the "Schlierenmethode" every kind of rays emitted by the source helps to bring out the same irregularities of the medium by ordinary refraction; as a rule no color-phenomena are to be seen, the dispersion of most media being small compared with the average deviation of rays. The chromosphere gases, on the other hand, are to be seen in characteristic colors, because they have an exceptionally high or low refractive index for particular sorts of light. In this case the dispersion is great in comparison with the average deviation of the rays.

Momentarily disregarding the self-radiation of the gases in the solar atmosphere we shall—if the slit is radially adjusted—find those chromosphere lines to be longest and brightest which show the greatest anomalous dispersion. We have seen that the two sodium lines show considerable difference in their respective powers to call forth this phenomenon. Let us make the pretty safe supposition that also the different hydrogen lines and the other chromosphere lines show analogous individual differences and we have the explanation why in the chromosphere spectrum some lines of an element are long and others short, and why the relative intensity of the lines of an element is so different in this spectrum from that in the emission spectrum or in the Fraunhofer absorption spectrum. A careful examination of the anomalous dispersion of a great number of substances will, of course, have to be made before it can be made out in how far our view will account for the facts already known or yet to be revealed in the chromosphere spectrum. Amongst other things it must then appear whether those elements whose lines are most conspicuous in the chromosphere light do actually cause uncommonly great anomalous dispersion—a wide field for experimental research, the exploration of which has only just commenced.

On the other hand, as regards the self-luminosity of gases, Lockyer's ingenious experimental method of long and short lines affords us an invaluable help to investigate what is the influence of the temperature (and the density ?) of the radiating substance on the emission spectrum. So it seems possible to make out by experiment whether it is radiation or refraction to which the different chromosphere lines are most probably due.

This decision ought, of course, to be founded on a most accurate knowledge of the character which each of the spectral lines of the solar atmosphere exhibits in different circumstances. The coming total solar eclipses offer a good opportunity to observe the chromosphere spectrum minutely, little disturbed by the dazzling light of the photosphere. Especially it is to be hoped that some good spectrograms will be obtained with high dispersion apparatus.

Let us now consider from the point of view of anomalous dispersion the well-known "reversing-layer" which in total eclipses causes the so-called "flash." We have seen before that the theory of dispersion assigns anomalous dispersion to all waves whose periods lie near each characteristic vibration-period of a substance; but the amount of the anomalous dispersion may be slight. In such a case the arrows, in an experiment similar to that described for sodium-light, would be short and narrow, but, for all that, of great intensity. If, therefore, such substances exist in the solar atmosphere even at great distances from the photosphere, with irregularities in density similar to those assumed for sodium, hydrogen, etc., the anomalous refraction will betray the presence of those substances merely in the immediate vicinity of the edge of the Sun's disk, and only during a few seconds at the beginning and the end of the totality of an eclipse.

This view of the subject makes it a matter of course that the lines of the flash should be very bright; for properly speaking it is not chiefly the radiation emitted by the vapors that we observe, but photosphere light of pretty much the same wave-length. Nor is it necessary that the gases in those places should be of extraordinarily great density, or that their presence should be restricted to a thin reversing layer — one of the most mysterious things the solar theory has led up to and one which astronomers have tried to escape in various ways.

The light of the chromosphere and of the flash lines may be symmetrically distributed on either side of the corresponding Fraunhofer lines; if so, they seem to coincide with the latter; but in certain places of the limb the case must arise that the bright lines would appear to have shifted their position with regard to the absorption lines. For in proportion to the distribution of the density of the vapors, it will be, in turn, especially the rays with very great refractive index (on the red side of the absorption lines) and those with very small refractive index (on the violet side of them) that are curved towards us.

As, upon the whole, the density of the gases of the solar atmosphere will decrease rather than otherwise in proportion as they are farther from the center, it may be expected (according to what we observed with regard to Fig. 4) that the bright lines will oftener shift their position with respect to the Fraunhofer lines in the direction of greater wave-lengths than in that of smaller.

These details will probably become clearly visible in the eclipse-photograms obtained with slit-spectrographs with great dispersion. It is not impossible that in many of the chromosphere lines a dark core may be seen.

Summarizing what we have said, we maintain the following position with respect to that part of the solar atmosphere situated outside what is called the photosphere.

The various elements whose presence in that atmosphere has been inferred from spectral observations are much more largely diffused in it than has generally been assumed from the shape of the light phenomena; they may be present everywhere, up to great distances outside the photosphere, and yet be visible in a few places only; their self-radiation contributes relatively little to their visibility (with the possible exceptions of helium and coronium); the distances, at which the characteristic light of those substances is thought to be seen beyond the Sun's limb are mainly determined by their local differences of density and their power to call forth anomalous dispersion.

In conclusion I wish to say a few words concerning phenomena presented by the Sun-spots. In the spectrum of these spots many of the Fraunhofer lines appear considerably broadened (see, *e. g.*, the diagram in Lockyer, *Chemistry of the Sun*, p. 100). The cause for this has been sought in the presence of very dense absorbing gases, and the broad bands have been attributed exclusively to absorption. The question is whether the second conclusion that we have drawn from the phenomena of refraction in a sodium-flame (p. 190) is not applicable here.

We proceed from the opinion that in a Sun-spot are found great differences of density dependent on strong vertical currents or, according to Faye, on vortex movements in the atmosphere. The phenomenon is commonly localized in the level of the photosphere, at all events, not far above or below it. Now if the entire body situated within the photosphere actually forms a sharp contrast with the outer atmosphere, and if its surface radiates to every side an almost equally intense light with a continuous spectrum, the broadening of the Fraunhofer lines and the darkness of the spots cannot be accounted for by merely attributing the spots to differences of density. The phenomenon must then be set down to differences of temperature, smaller radiating power, condensation, stronger absorption, etc.

Matters are different, however, if A. Schmidt's view is taken to be the correct one, according to which the Sun's limb is an optical illusion caused by regular refraction in a gradually dispersing, nowhere sharply bounded, mass of gas. In this theory the apparent surface of the photosphere is merely a critical sphere, characterized by its radius being equal to the radius of curvature of rays of light traveling along its surface horizontally; there is not the least question of any discontinuity in the distribution of matter on either side of this spherical surface; inside as well as outside the critical sphere the average density of matter and its radiating power increase gradually towards the center, and it is only at great depths that the condition of matter need be such as to emit a continuous spectrum.

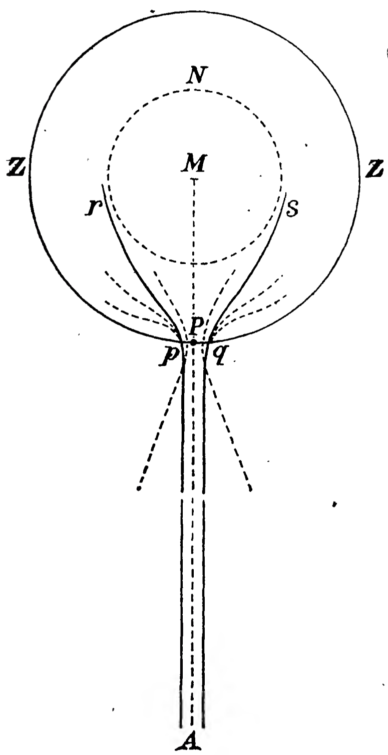


FIG. 5.

Let the circle ZZ' in the diagram (Fig. 5) be the section of the critical sphere with the ecliptic, and let the Earth be in the direction MA. Suppose a spot visible in the center of the Sun's disk; it is seen projected on the critical sphere in P. Now let us suppose that the density increases all around from the center P of the spot, locally producing there cylindrical, rather coaxial, layers with the line of vision for basis. Rays pA and qA suffering normal refraction, may, as is easily seen, have traversed in the Sun the paths rp, sq, and may, therefore, originate, not, it is true, from the most luminous center, but yet from pretty intensely radiating parts of the Sun. They yield the white light of the umbra and of the penumbra, which, though standing out dark against the other parts of the Sun, yet are relatively bright enough.

Slight irregularities in the distribution of density around P render it possible that parallel to PA there emerge rays that have followed other paths which, nevertheless, will essentially be included in the solid angle *rPs*.

But rays which have undergone anomalous dispersion and yet reach our eye in a direction parallel to *PA*, must have proceeded from a much greater diversity of directions, and need not, therefore, have been emitted in such numbers by the intensely luminous central part of the Sun.

We may also put the matter thus: Of all the light, coming from the intensely radiating nucleus of the Sun (to which may be reckoned all that lies within the sphere *N*) and emerging from the vicinity of *P*, those rays, whose refractive index is abnormally high or low will be more effectually dispersed in all directions, owing to the local differences of density, than rays with a normal index.

The consequence is that the observer, looking in a given direction towards *P*, will see less of those abnormally refracted rays than of the other light. Those rays will, therefore, seem absent in the spectrum of the spot: the Fraunhofer line is seen broadened.

Whereas our considerations concerning the chromosphere light were made independently of any theory of the nature of the photosphere, the present broadly outlined explanation of the phenomenon of the Sun-spots is to a certain extent based on the theory of Schmidt — with which, in fact, it stands or falls.

If subsequent investigations should prove the lines that generally appear broadened in the spectra of the spots, and those which call forth strong anomalous dispersion, to be identical, this would support Schmidt's solar theory.

For the rest it is easy to see that henceforth the principle of anomalous refraction will have to be considered side by side with that of Doppler in every instance when an explanation is required of the many irregularities that have been observed in certain Fraunhofer lines, both near the Sun's limb and in faculae and spots; *cf.* the illustrations in Lockyer's *Chemistry of the Sun* pp. 122 and 123; Young, *The Sun*, pp. 157 and 210; Scheiner, *Die Spectralanalyse der Gestirne*, p. 349.

Such phenomena *may* be caused by refraction, whereas hitherto the only possible explanation was sought in the assumption of tremendous velocities in the line of vision.

The foregoing considerations may suffice to show that anomalous dispersion naturally accounts for a great number of solar phenomena. At any rate no future theory of the Sun can ignore the laws of refraction.