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Physics. — *"The lines H and K in the spectrum of the various parts of the solar disk"*. By Prof. W. H. Julius.

§ 1. *Causes of line-shifts.*

There are at present four causes known, by which bright or dark lines of the solar spectrum may be displaced with respect to the position of the corresponding emission lines, as observed in laboratory experiments: radial motion, pressure, magnetic fields, anomalous dispersion. Which of these causes is likely to be the effective one, in each special case, can only be decided by comparing from a physical point of view the possibility of the conclusions to which the different suppositions lead us. If, e.g. we try to explain, by each of the four principles, the strong line-displacements often observed in the spectrum of prominences, it soon appears that both the second and the third principle are unable to give satisfactory solutions of the problem, so that, on further research, we shall only have to choose between the first and the fourth. On the other hand, the general displacement of the Fraunhofer lines toward the red, increasing from the centre to the limb of the solar disk, can be accounted for neither by Doppler's principle, nor by the Zeeman effect; so the interpretation of the phenomenon as a pressure effect has to be compared, in its consequences, with the interpretation on the basis of anomalous dispersion.

In a few cases there is scarcely any reason for doubt about the origin of certain line-displacements. Nobody will hesitate to ascribe the systematic differences between the spectra of the east and west limb of the sun to motion in the line of sight; nor question the magnetic origin of doublets and triplets in the spot-spectrum, which show the polarisation phenomena characteristic of the Zeeman effect. But such cases, where even at first sight only one explanation seems possible, are rare. It would be rash, e.g. to make magnetic forces at once responsible for the total widening of spot-lines, while other causes, that also produce widening, are known. As a rule, various influences co-operate; then the probably effectual cause of a solar phenomenon will only be brought out as such indirectly, by exclusion, that is, after other explanations have entangled one in ideas, clashing with general physical laws. And the remaining explanation will of course be the more probable, the better it joins some theory, already giving a coherent view of many other solar phenomena.

§ 2. *Phenomena exhibited by the calcium lines H and K.*

A remarkable case of systematic displacements, occurring with the calcium lines H and K, was first described by DESLANDRES in 1894, then by JEWELL in 1896, and has recently been investigated very carefully on Mount Wilson by CHARLES E. ST. JOHN [1]), and at Meudon by DESLANDRES [2]). The main character of these phenomena is, that in the spectrum of the central parts of the solar disk the narrow dark lines H_3 and K_3 are displaced toward the red, the wider, bright lines H_2 and K_2 toward the violet; that these displacements decrease as we approach the limb, and that, on the other hand, the width of those lines increases from the centre to the limb. For further particulars we refer to the paper by ST. JOHN.

The peculiarities of the phenomenon cannot possibly be explained when pressure or magnetic forces are supposed to be the effective cause. ST. JOHN, who takes no notice of anomalous dispersion as a possible cause, is therefore so absolutely convinced of the radial-motion nature of the phenomenon (and so are DESLANDRES and JEWELL), that he describes the results of his excellent observations under the title: "The general circulation of the mean- and high-level calcium vapor in the solar atmosphere".

We are going to show in the following pages, however, that all of the properties of the lines H and K, described by DESLANDRES and ST. JOHN, can be interpreted as consequences of anomalous dispersion. Thus, fortunately, one is *released from the necessity* of assuming, that in the solar atmosphere two opposite vertical currents of calcium vapour are continually kept up, meeting or perhaps passing or penetrating each other with velocities 30 or 60 times greater than the velocity of the most violent terrestrial blasts — and, marvellously, leaving the hydrogen and the other gases of the chromosphere unaffected! The explanation on the basis of anomalous dispersion does not involve such difficult physical notions, and offers the advantage, that it easily fits a theory, already connecting a great many other phenomena.

§ 3. *The influence of anomalous scattering on the distribution of light.*

The light coming from the lower strata of the sun, and having to traverse an extensive absorbing atmosphere, loses intensity not only by absorption, but also by *scattering*. It is true that radiant energy, when scattered, only alters its direction of propagation, not its nature (whereas, when absorbed, it suffers a change); so the scattered energy must finally quit the celestial body in the original form. But because part of it always returns to the source, we may

1) CHARLES E. ST. JOHN, Astrophysical Journal, **32**, 36—82, (1910).
2) H. DESLANDRES, C. R. **152**, 233—239, (1911).

imagine that scattering *retards* radiation, and thus diminishes the output per unit time.

For kinds of light differing little in wave-length from the absorbed light, the coefficient of scattering is considerably greater than for light of the remaining parts of the spectrum, its value being proportional to the square of the refraction constant (according to RAYLEIGH), and the latter having great absolute values in the vicinity of absorption lines. Consequently the neighbourhood of the absorption lines must be more weakened by scattering, than the rest of the spectrum; which means, that the darkness of the Fraunhofer lines is partly due to anomalous dispersion.

How this conception of the solar spectrum follows from the theory of electrons, has been shown elsewhere[1]). We must now recall to mind some of the results there obtained.

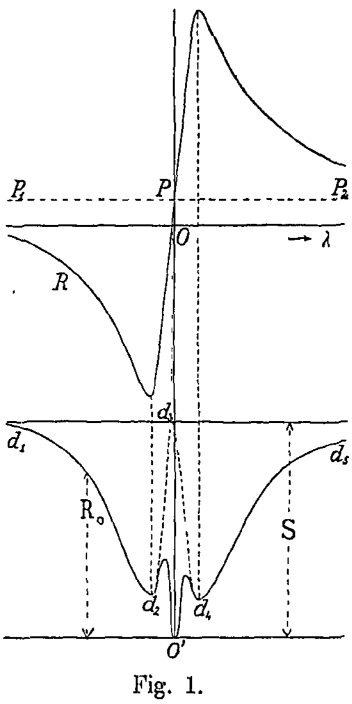

Fig. 1.

The curve representing the refraction-constant $R = \frac{n-1}{\Delta}$ as a function of λ, has in the region of an absorption line the shape, drawn in the upper part of fig. 1. On both sides of the line OP it approaches the almost horizontal line P_1P_2, by which the course of the refraction constant of the medium would be represented if there were no absorption line at $O(\lambda = \lambda_0)$. If we compare with each other the absolute values of the ordinates of the curve R in points, situated at equal distances left and right of O, we find them always greater on the right side than on the left side. All effects, therefore, that increase with the absolute value of $n-1$, will manifest themselves more strongly on the red than on the violet side of the line. This applies 1st to the loss of light by scattering; 2nd to the intensity of the scattered light; 3rd to the rate of variety of brightness that may result from ray-curving, when there are density gradients in the medium. It follows, that on the average (i. e. apart from local irregularities) both the Fraunhofer

[1]) W. H. JULIUS Selective absorption and anomalous scattering of light in extensive masses of gas. Proc. Roy. Acad. Amst. XIII, 881, (1911).

lines and the chromospheric lines are asymmetrical with regard to the exact positions of the emission lines, so as to have their "centres of gravity" somewhat displaced toward the red. One can easily show that this effect must increase from the centre toward the limb of the solar disk. Its character corresponds exactly to that of the systematic line-displacements, described in recent years by HALE and ADAMS, FABRY and BUISSON, and others, and considered by those investigators as consequences of pressure in the reversing layer. Objections to their interpretation, and arguments in favour of our explanation which is based on the shape of the dispersion curve, are to be found in former communications [1]). The part of the dispersion curve, lying between the minimum and the maximum, had not yet been taken into consideration then, that region being too narrow, with most Fraunhofer lines, to be observable by means of the spectral apparatus at present in use. But we are now extending our discussion to that middle part of the curve, which may perhaps reveal itself within a few very wide lines.

The lower part of fig. 1 (derived from the dispersion theory) shows, for the environment of a single absorption line, the intensity R_0 of the light transmitted by the solar atmosphere, if, for all waves considered, the intensity of the incident light is supposed to be S. The influence of *scattering* appears from the course of the (partly dotted) curve $d_1 d_2 d_3 d_4 d_5$; that of *absorption* from the shape of the additional part lying between d_2 and d_4, and showing a steep drop at O'. Only a few gases, strongly represented in the solar atmosphere, seem to exhibit so strong an absorbing power, that the minimum and the maximum of the dispersion curve are sufficiently distant from each other to make the phenomena, characteristic of the interval, perceptible.

Where this happens to be the case, we may expect to find, according to the dispersion theory [2]), that the "centre of gravity" of the central dark line is displaced toward the red, and that the apparent emission line, which is due to the scattering effect passing through a minimum at d_3, shows a displacement toward the violet. This simple deduction is in perfect agreement with the general phenomenon, observed by DESLANDRES, JEWELL, and ST. JOHN with the lines H_3 and K_3, H_2 and K_2, in the spectrum of the central parts of the solar disk.

§ 4. *The influence of anomalous refraction on the distribution of light.*

In order to find out how the effect will change as we approach

1) Proc. Roy. Acad. Amst. XIII, p. 2, (1910); "Le Radium", VII, Oct. 1910.

2) Proc. Roy. Acad. Amst. XIII, p. 895, (1911).

the limb of the sun, we must fix our attention on another peculiarity of the propagation of light through matter. Indeed, anomalous dispersion implies not only anomalous *scattering*, but also, wherever the density of the medium is unequal, anomalous *refraction*.

Let us, for the present, leave out of consideration those "large-scale irregularities", characterized by more or less "systematically arranged" density gradients (such as probably exist in sun-spots) [1]), and imagine the average condition of the solar atmosphere to be like that of hot gases above a fire, i. e. a complex of irregular density gradients strongly varying from point to point in direction, magnitude, and sign. A very extensive layer of gas, thus constituted, must in some way act as a turbid or scattering medium. The optical effect produced by such an atmosphere will be comparable to what we observe when viewing a luminous surface through a plane-parallel glass tank in which, for instance, water and glycerine have just been stirred, but are not perfectly mixed yet. This "scattering by refraction" is, like molecular scattering, specially strong for kinds of light from the vicinity of absorption lines. So the effect of anomalous refraction is in many respects very similar to that of anomalous scattering, and will in so far only strengthen the latter.

But we should not overlook the difference between the two processes. The intensity of the effects of anomalous refraction depends on the degree in which there happens to exist *variety of density* in the medium. So it may be quite different at different places on the solar disk [2]), whereas the intensity of the effect of molecular scattering is more equally distributed, only increasing gradually from the centre to the limb. And, secondly, we must notice that the *direction* of the density gradients may strongly influence the intensity of the light emerging from the solar atmosphere along a given line. This circumstance too causes a kind of inequality in the distribution of the light, such as molecular scattering could not produce.

We are now prepared to inquire into the changes, which the distribution of the light in general, and the aspect of the calcium lines in particular, must show when we pass from the centre to the limb of the solar disk.

Those changes are of course closely connected with the fact, that in the central parts of the disk the main source of light has an almost symmetrical position behind the atmosphere, but not in the non-central parts.

1) Proc. Roy. Acad. Amst. XII, p. 273, (1909).

2) The irregular distribution of the light in spectro-heliograms can be explained n this basis.

A point M somewhere in the atmosphere of the sun will be seen on the centre of the disk by an observer stationed on the line MA; but an observer on MB will see it not far from the limb. To the second observer the region round M appears much less bright than it does to the first one. This proves, that M receives less light (perhaps only half as much) along the direction bM than along aM. How, in a point M, the intensity of the irradiation by a definite kind of light depends on the direction of incidence, can easily be found, provided that we know the average distribution of the brightness on the solar disk, for the light in question.

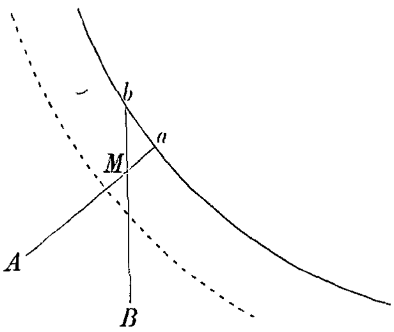

Fig. 2.

In fig. 3 PQ shows the gradual decrease of the brightness from the centre C toward the limb R of the solar disk for waves between 405 and 412 $\mu\mu$, according to spectro-photometric measurements by H. C. VOGEL[1]). Let RNC' represent a section of the photospheric surface, and suppose an observer to be placed at a great distance in the direction CC'; then it is clear that e.g. from N — that is, in a direction making an angle ANB ($= NCC' = \varphi$) with the normal to the photosphere, — an average quantity of light proportional to the ordinate mn of the $P'Q'$-curve, emerges from the solar atmosphere.

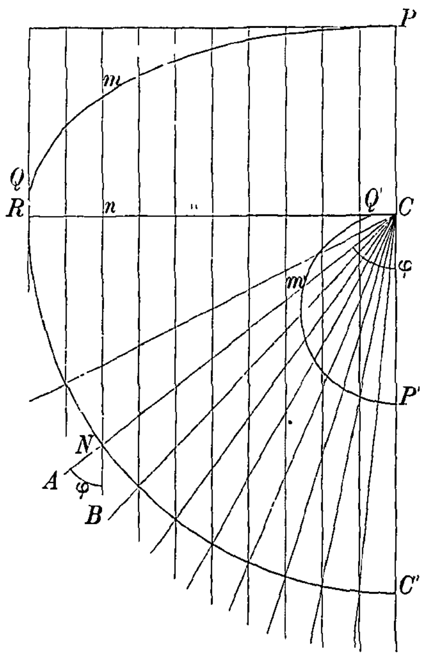

Fig. 3.

We now define a point m' on the radius vector CN by making $Cm' = mn$, and do the same on the other radii of the section RNC'. Thus a curve $P'Q'$ is obtained, representing the transmissive power of the solar atmosphere for the selected kind of light, as a function of the angle of emergence φ. With the aid of this figure we may now proceed to the construction

[1]) H. C. VOGEL, Ber. der Berl. Akad., 1877, S. 104.

the "irradiation-curve" for a point M (fig. 4) situated in e outer layer of the solar mosphere. For that purpose e only have to take on each ıe MV, lying within the ıgle $H'MH$ and cutting the ıotosphere at an angle φ with e normal, a distance equal to at polar co-ordinate of the ırve $P'Q'$ (fig. 3), which cor-

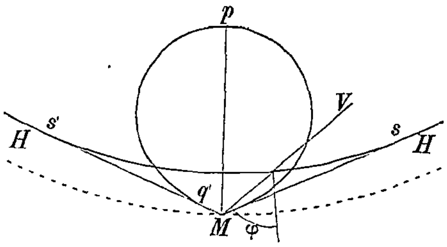

Fig. 4.

sponds to the same value of φ. Joining the end-points of the ctors thus defined, we obtain the required irradiation curve qpq'. differs only slightly in shape from $P'Q'$, and, as is easily seen, ould preserve very nearly the same character if M were chosen a lower level [1]).

Now looking for an *explanation* of the general decrease of brightss toward the limb, it is only natural to make scattering respon-)le for the phenomenon (both molecular and refractional scattering). fact, *all* kinds of light are more or less liable to scattering, whereas, ry probably, absorption only extends to waves having the same, almost the same frequency as the free vibrations of the electrons the solar gases [2]).

The widening of the Fraunhofer lines toward the limb proves at the gradual decrease of intensity from centre to limb is greater r kinds of light suffering anomalous dispersion, than for the less frangible light from blank spaces of the spectrum. Accordingly, if e construct the irradiation curve of a point M of the solar nosphere for one of the strongly refrangible kinds of light from e vicinity of an absorption line, it will show a more oblong, oval ape than the curve that has been deduced, in fig. 4, from

[1]) In this reasoning only the *observed* fact of the decrease of brightness vard the limb was taken for granted, no hypothesis regarding the cause of ıt phenomenon being required so far. The result. therefore, includes the full tification of the assumption on which our earlier considerations about the)pagation of light through the solar atmosphere were based, viz. that the ensity of the light, incident on a small region M of that atmosphere, varies her strongly with the direction (Proc. Roy. Acad. Amst. XII, 268, (1909)). Some rophysicists objected to that view. Founding their refutation on the opinion, that)oint of the solar atmosphere receives equal amounts of light (per unit of spacegle) from all directions meeting the photosphere, so that a circle $s'ps$ would)resent the irradiation curve, they evidently left the above-mentioned elementary ult of the observation of the sun entirely out of consideration.

[2]) Proc. Roy. Acad. Amst. XIII, 888. (1911).

VOGEL's observations on average violet light. This means, that for instance such waves as correspond to the places d_2 or d_4 of fig. 1, will reach a point M with an intensity that varies in a stronger measure with the direction in which they left the photosphere, than does the intensity of the average light.

Those very waves (near d_2 or d_4) are at the same time especially liable to *changing their direction of propagation* when there is a density gradient at M. If we were not concerned with anomalous *refraction*, but only with anomalous *scattering*, we should find that a definite kind of light would have a constant intensity, at any definite distance from the limb. But the refraction causes inequality. And the chance of observing a conspicuous variety of brightness, when looking at a region M of the solar atmosphere, which projects on the disk at a given distance from the limb, increases with the absolute value of $n-1$. By this circumstance we can e. g. explain a prominent feature of the spectroheliograms obtained by HALE and ELLERMAN [1]), viz. the gradual increase of the contrasts in a series of photographs of the same region, taken with waves, selected within K_1 at decreasing distances from K_3.

§ 5. *The co-operation of the two before-mentioned influences.*

The above discussion of the consequences of anomalous dispersion suggests the following interpretation of the variable, bright K_2-line, generally supposed to be an emission line.

There are two causes by which the brightness may increase on approaching K_3.

One of them depends on the presence of the two small (unequal) maxima of the R_0-curve in fig. 1, indicating a diminution of the loss of light by scattering. This influence acts almost equally in all points situated at equal distances from the centre; it is strongest on the middle parts of the disk; for in proportion as we approach the limb, the scattered light itself will contribute a greater share in the total emergent beam, thus levelling the curve and reducing the importance of the two small tops. The part of the effect, due to this first cause, is weak any how, even on the central parts of the disk, but of a constant nature: it always yields a narrow, double K_2-line, displaced toward the violet, and produces a displacement of K_3 toward the red.

The other cause depends on refraction in irregular density gradients. On the middle of the disk, refraction can only result in *diminution*

[1]) Hale and ELLERMAN. The Rumford Spectroheliograph of the Yerkes Observatory. Publications of the Yerkes Observatory, Vol. III, Part I, 1903.

of the original brightness, and this effect must be strongest for the most refrangible waves corresponding to d_2 and d_4; K_2, which is situated there between those wave-lengths, is relatively narrow. But at some distance from the centre, where for every wave-length the average brightness is less than at the centre, density gradients may bring about, that light, emitted normally by the photosphere, curves toward the observer, thus producing a local increase of brightness.

Now again we fall back upon the most refrangible kinds of light, those at d_2 and d_4, as the ones that will be able to produce the latter effect in the strongest degree. Putting it otherwise: on the non-central places of the disk *refraction* will here and there contribute bright patches to the formation of the K_2-line, whose maxima of intensity have the greatest chance to correspond to the wave-lengths at d_2 and d_4. This effect combines with the before-mentioned scattering-effect. The components of K_2 must therefore, on an average, be farther apart than on the middle of the disk.

Proceeding toward the limb, the first part of the effect, that which is due to the dotted part of the scattering curve, diminishes, as already stated; while the second part, caused by refraction, gains in importance. Consequently the average distance between the components of K_2 increases, and, at the limb, becomes equal to that between d_2 and d_4. The bright components are not interrupted there by dark patches, as elsewhere on the disk, because at the limb the strongly *scattered* waves always enhance the brightness.

The influence of the two little tops of the R_0-curve, which on the middle of the disk determined the K_2-line, has disappeared near the limb; hence K_3 is wider than at the centre. Moreover, the displacements of K_3 and K_2 to the red and the violet respectively have gradually decreased on approaching the limb; for they depended on the asymmetry of the little tops. The points d_2 and d_4, determining the average places of the components of K_2 at the limb, are situated at equal distances from the real absorption line.

§ 6. *Weak points of the new and of the old explanation.*

While, all in all, these conclusions drawn from the dispersion theory show a very close agreement with the results of the observations, we should by no means neglect to pay due attention to the points where discordance exists or seems to exist. Only if searching for defects, one has a chance to improve one's views.

So we must notice that, if scattering and irregular refraction determine the phenomenon, we have some reason to expect asymmetry of K_2 near the limb; and if we were right in assuming the absolute value of $n-1$ to be greater at d_4 than at d_3, the red component should be a little stronger than the violet one. ST. JOHN, however, states [1]: "On the plates 1 mm. from the limb the emission components are very broad and strong, and, as far as the eye can judge, symmetrical". But on measuring the *width* of the components on some 30 selected plates, he found the violet one on the average 0,0074 Å wider than the red one. Surely the difference is small, but if it proves to be genuine, not accidental, our theory cannot, in its present form, explain the phenomenon — unless we are just here perhaps concerned with the case of asymmetry of the dispersion curve, treated of in § 3 of my former communication [2]).

Another case in which our theory perhaps falls short, is the following.

From published reproductions of spectrograms, obtained at Meudon and on Mount Wilson, I get the impression that the average distance between the brightest places of the K_2-components is greater at the limb than on very bright flocculi and faculae situated e.g. halfway between centre and limb. Now, according to our explanation, the position of the brightest patches of the components ought to be almost entirely determined by the position of the points d_3 and d_4, also in the spectrum of those brightest flocculi, because the part of the brightness which is due to the small intermediate tops of the R_0-curve is relatively slight in flocculi. That is: we should expect K_2 in the spectrum of very bright flocculi and faculae to be on the average not less wide than at the limb [3]). If the study of original plates confirms our suspicion that in this case the results of the observation contradict the theoretical conclusions, we shall have to correct the theory, or, if that is impossible, to reject it.

Finally attention must be called to some consequences resulting from the explanation given by DESLANDRES, JEWELL and ST. JOHN of the phenomena exhibited by the H and K lines.

Among the greatest difficulties into which we are led by ascribing the line-displacements in question to ascending and descending currents, is in my opinion the one, already mentioned in the beginning of this paper: How is it possible, that in those violent vertical hurricanes of calcium vapour prevailing over the general surface of the sun, other gases of the chromosphere are not involved at all?

1) ST. JOHN. l. c. p. 54.

2) Proc. Roy. Acad. Amsterdam, XIII, 885, (1911).

3) In making the measurements, from which the gradual increase in width of K_2 and K_3 on approaching the limb has been deduced, ST. JOHN intentionally avoided the brilliant facular and floccular regions. Cf. l.c. p. 48 and 50.

Besides, the question arises, what can be the nature of the forces, giving such velocities to the co-existing rising and falling currents, and acting especially on *calcium*, not, or at least in a much lesser degree, on other gases? Some additional hypothesis is badly wanted here.

There are more difficulties, that one cannot avoid without introducing special hypotheses. The widening of K_2 towards the limb is explained by the continuous increase of the depth of the layer of radiating calcium vapour in the line of sight on approaching the limb. It is supposed that a sensible part of the beam of calcium-light, reaching the observer, has been able to travel a distance of 16000—62000 kilometers [1]) in a nearly straight line through a layer of the selectively absorbing solar gases, in which the average pressure is evaluated at one (terrestrial) atmosphere [2]). This conception seems to be opposed to the generally accepted theory of scattering and absorption of light. Moreover, one would expect, on the basis of the same explanation, to find the absolute brightness of K_2 increasing in passing from the centre to the limb. This, however, does not come true. Only in comparison with the neighbouring parts of the spectrum, K_2 increases in importance, but its absolute brightness decreases decidedly. In order to obtain spectrograms of nearly equal photographic density, St. John had to make the exposures 4 to 5 times longer at the limb than at the centre. The current explanation of the phenomena therefore requires the indication of an additional agent or process, by which the radiation of the chromosphere, although supposed to increase in passing from the centre to the limb, appears to decrease. One might e.g. assume the existence of a medium, surrounding the chromosphere in a rather thin layer, and having the property of absorbing all kinds of light in a certain degree

Similar additional hypotheses need not be introduced, if we explain the phenomena, exhibited by the calcium lines in the spectrum of the various parts of the solar disk, by means of the theory of the propagation of light through extensive masses of gas.

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[1]) St. John, l. c. p. 66.
[2]) St. John, l. c. p. 43.