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RADIAL MOTION IN SUN-SPOTS?

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In two elaborate and interesting papers, bearing the above title without the interrogation point, St. John[1] has very skilfully discussed his observations on line displacements in sun-spot spectra from the point of view that the efficient cause of those displacements is motion in the line of sight. Although at the end of the second paper he also devotes a few pages to criticizing the theory that attempts to explain such phenomena on the basis of anomalous dispersion, he could not, of course, do full justice to a point of view differing so radically from his own. I therefore thought it my duty to defend the attacked position which is by no means so weak as he represents it.

THE INTERPRETATION BASED ON THE DOPPLER EFFECT

St. John's investigation relates to eleven spots in positions between 25° and 60° from the center of the disk. The slit of the spectrograph was parallel to the radius of the solar image, passing through the center of the spot umbra. Nearly all of the 506 lines included in the measurements are displaced to the red on the edge of the penumbra nearest the limb, and to the violet on the opposite edge; only 13 lines show the reverse effect. In agreement with

[1] *Mt. Wilson Contr.*, Nos. 69 and 74; *Astrophysical Journal*, **37**, 322, and **38**, 341, 1913.

Evershed, who discovered the phenomenon in 1909, St. John concludes that the displacements are due to radial flow of matter tangential to the solar surface, generally directed from the center of the spot outward, but, on the contrary, inward in the case of the 13 exceptional lines.

If this interpretation of the displacements were free from serious difficulties it would be unnecessary to propose other views of the subject. It is a fact, however, that there are great difficulties; hence the pro and con of rival theories may well be submitted to the consideration of astrophysicists.

The displacements on which St. John's conclusions depend are of the order of magnitude 0.020 A, only very few exceeding 0.040 A. It certainly testifies to that author's experimental proficiency as well as to the power of the Mount Wilson apparatus that on such minute quantities a regular investigation can be based; but at the same time the conditions of the research warn us against putting too much confidence in the individual observations. On p. 4 of *Contribution No. 69*, St. John explains why the mean deviations (given in the sixth column of his Table I) from the mean displacements calculated for every line are so considerable. Trustworthy results can therefore be expected only from those considerations in which the statistical treatment includes a sufficiently great number of observed displacements, whereas the reliability of apparent relations rapidly decreases with the number of measurements from which they are deduced.

A survey of the whole series of measurements led St. John to the discovery of two very important and striking laws: (1) the displacements increase with increasing wave-length; (2) the displacements progressively decrease with the increase of line intensity.

Tables II and III,[1] illustrating these laws as they appear in the measurements on 193 iron lines of intensity 1 to 8, are reproduced here for convenience of reference. In the upper section of Table II the displacements are as measured; in the lower section they are reduced to a common wave-length, λ 5000. This reduction has been applied by St. John on the ground that, if the displacements

[1] *Mt. Wilson Contr.*, No. 69, pp. 16–17; *Astrophysical Journal*, **37**, 337–338, 1913. I keep the numbers II and III for these tables, so that in the present paper there is no Table I.

are due to the Doppler effect, they should be proportional to the wave-length. He therefore divides every displacement by the fraction λ/5000; the values thus obtained form the lower section of the table; they should be equal for lines of equal intensity.

TABLE II

DISPLACEMENTS AND WAVE-LENGTH

Region	Mean λ	Intensity 1	2	3	4	5	6	7	8	Mean
Violet..........	4017	0.022	0.020	0.014	0.014	0.013	0.011	0.008	0.006	0.014 A
Yellow-red......	6121	.032	.030	.032	.024	.028	.024	.019	.016	.026
Violet..........	4017	.026	.024	.019	.018	.017	.013	.011	.008	.017
Yellow-red......	6121	0.027	0.024	0.026	0.021	0.023	0.020	0.015	0.013	0.021

TABLE III

DISPLACEMENTS AND LINE INTENSITIES REDUCED TO λ 5000

Mean λ	Intensity 1	2	3	4	5	6	7	8	No Lines	Mean Interval
4017............	0.026	0.024	0.019	0.018	0.017	0.013	0.011	0.008	81	0.003 A
4992............	0.030	0.026	0.026	0.025	0.018	0.016	0.006	0.007	69	0.003
6121............	0.027	0.024	0.026	0.021	0.023	0.020	0.015	0.013	43	0.002
Wtd. mean......	0.028	0.025	0.023	0.021	0.019	0.016	0.012	0.009	......	0.003
Vel. km/sec......	1.68	1.50	1.38	1.26	1.14	0.96	0.72	0.54	......	0.18

Now, I think it impossible to agree with St. John when he concludes that the results collected in Table II "seem decisively in favor of an effect varying as the wave-length" and that "the decrease from 0.012 A to 0.004 A in the mean difference [between the average displacements in the violet and in the yellow-red regions] when the displacements are reduced to a common wave-length indicates that the observed differences are due to the Doppler effect, and that we are dealing with real movements of gases in the reversing layer." The table gives plenty of evidence, on the contrary, that the displacements are by no means proportional to the wave-length. Indeed, in every intensity class they appear to increase more rapidly than the wave-length. Moreover, the rate of increase with wave-length is far from regular, for if we transfer the series of displacements relating to mean λ 4992 from Table III to the upper section of Table II and put it between violet and yellow-red, we see that for lines of low intensity the rate of increase of the displacements is in general more rapid between mean λ 4017 and λ 5000 than between λ 5000 and mean λ 6121, whereas for lines of high intensity the reverse seems to obtain.

There would not be any objection, of course, to advancing the *hypothesis* that the Doppler effect is involved in the phenomenon, and to try additional hypotheses in order to account for the systematic and the irregular deviations[1] from proportionality between displacement and wave-length. I deny only that the data included in the above tables give any decisive indication in favor of the view which considers the Doppler effect as the principal cause of the diplacements. Neither do the same data contain a positive proof that the rival explanation which is based on anomalous dispersion is the right one; but, as will be shown in the second section of this paper, the latter interpretation deserves notice and has more features that recommend it than the former if the value of both be judged by the criteria so well formulated by St. John at the beginning of the section on p. 14 of *Contribution No. 74.*

Reverting to St. John's discussion of the above tables, we remark that Doppler's principle alone has nothing in it to explain the remarkable and well-established progressive decrease of the displacements with the increase of line intensity. A new hypothesis, therefore, had to be introduced. St. John assumes that the weaker iron lines originate at the lower level, so that the displacements would increase with depth. By this assumption he intends to insure a *progressive* change in the velocity of outflow of matter with change of level, and at the same time opens a way to account for the fact that the displacements do not exhibit the otherwise expected proportionality with the wave-length, but increase more rapidly. For it might be that among the lines of the same intensity those belonging to the yellow-red region of the spectrum originate at a lower level than those belonging to the violet region, a difference which the author calls a natural consequence of the scattering of light by small particles.

[1] Cf. Fig. 6, p. 23.

Many spectroscopists, however, will shrink from accepting this bold hypothesis of the "Iron Scale" which supposes the various intensities of the solar lines of an element to indicate the levels where they originate. In the laboratory, the absorption spectrum of a gas (for instance, of NO_2) shows strong and weak lines at the same time; it is not easy to admit with St. John[1] that in the sun "the absorbing centers effective for lines of different intensities of a given element are apparently not identical and appear to be allocated in successive spherical shells." What are we to think, e.g., about the theories of series lines from this point of view?

But let us pass this difficulty, and see what the Doppler interpretation of these line-shifts results in.

All elements included in the investigation, except hydrogen, are moving from the axis of the spot vortex outward with velocities varying between 1.1 and 0 km per second. Hydrogen flows inward at a higher level, and so do special forms of calcium, magnesium, sodium, iron, and strontium, respectively represented by 3, 2, 2, 2, and 1 lines.

In general the horizontal velocities seem to be greatest near the outer edge of the penumbra. Multiplying the circumference of the spot by the distance between the lowest and the highest level of outflowing matter, we get the transverse section of the stream, in which the average velocity of the gases may be estimated at 0.7 km per second. The stream must be fed by a rising current in the center of the spot, the stream lines of which will progressively pass from a vertical to a horizontal direction. The vertical component of the motion would become the more conspicuous, the more a spot approaches the center of the solar disk; and as very probably the transverse section of the vertical current in the umbra is not much greater than that of the horizontal current near the outer edge of the penumbra, we should expect to find considerable displacements of most umbral lines toward the violet, especially in the spectra of spots located in the central parts of the disk. And in the penumbral spectra of eccentrically located spots the vertical component of the motion would have the effect of increasing the displacements to the violet and diminishing those toward the red.[2]

[1] *Mt. Wilson Contr.*, No. 74, p. 13; *Astrophysical Journal*, **38**, 353, 1913.

[2] The 13 exceptional lines are not considered here.

Definite indications of such vertical velocities are not mentioned, however. This, I think, is one of the most serious objections against the assumption that radial motion in sun-spots is the effective cause of the displacements in question. St. John suggests[1] that the levels where the vertical components of the velocities prevail are too low to be accessible to spectroscopic investigation. If this were true for the lines of intensity 00, it would not hold good for the lines belonging to higher levels, because their absorbing centers rise a long way through optically accessible layers. So the difficulty is not removed.

The opposite displacements of the 13 above-mentioned chromospheric lines are explained as indicating a radial inflow of chromospheric material into the spot. From the displacements which the lines H and K of calcium show in the spectrum of the umbra[2] it would follow that this gas is moving downward in the center of the spot with a velocity of 1.3 km per second. The other chromospheric gases are supposed to share the downward motion, although their lines appear not sufficiently displaced in the spectrum of the umbra to make the assumption plausible. The question where this chromospheric material goes after having reached the reversing layer finds no satisfactory solution in the results of the measurements; and it seems very difficult to reconcile the necessary consequences of an impact between the downward-rushing chromospheric matter and the upward-rushing matter of the reversing layer with the assumed relatively low temperature of the umbral region.

St. John attempts to corroborate his intensity-and-level hypothesis by considering the atomic weight of the elements in connection with the displacements of their lines in the spot spectrum. We may doubt whether the data suffice for the purpose. It is stated, e.g., that the lines of the heavy elements, such as barium, lanthanum, neodymium, cadmium, cerium, lead, and ytterbium, originate at lower levels than the lines of like intensity of iron;[3] but if we refer to Table I of the first paper we find that

[1] *Mt. Wilson Contr.*, No. 69, p. 24; *Astrophysical Journal*, **37**, 345, 1913.

[2] Cf. *Mt. Wilson Contr.*, No. 54, pp. 28–29; No. 69, pp. 24–25 and 27–28; *Astrophysical Journal*, **34**, 136–137, 1911; **37**, 345–346, 348–349, 1913.

[3] *Mt. Wilson Contr.*, No. 74, p. 6; *Astrophysical Journal*, **38**, 346, 1913.

the evidence is not so very strong. Lead, ytterbium, and cadmium are represented by only one line each, barium by two lines; these five lines really show larger displacements than the mean iron lines of like intensities. With lanthanum the conclusion has somewhat greater weight, because nine lines have been measured. Four of them (intensity 1) give the mean displacement 0.029 instead of 0.028 which would correspond to the iron scale; four lines of intensity 2 give 0.026 instead of 0.025, and one of intensity 4 gives 0.025 instead of 0.021. The differences are small (considering the great atomic weight of lanthanum), but in the required direction. With cerium, on the other hand, one of the two lines by which it is represented in the table shows a displacement 0.026 instead of 0.023 but the other one (intensity 1) gives 0.017 instead of 0.028 and thus points to a *higher* level. Of neodymium, finally, three lines have been measured; two of them (intensity 1) give the mean value 0.025 instead of 0.028 and one (intensity 2) gives 0.022 instead of 0.025, so that the lines of this element (atomic weight 144) would seem to originate on the average at a higher level than the iron lines of like intensity. An equally unfavorable account must be given of zirconium (atomic weight 91), for the displacements of six of its seven lines in the list would also decidedly, from the point of view of St. John's hypothesis, indicate higher levels than those corresponding to the iron scale.

It is possible, though not probable, that the large deviations which the mean displacements of individual lines often show with respect to the mean value corresponding to their intensity class and spectral region find a sufficient explanation in the extreme difficulty of the measurements. If, however, the accuracy attained would permit of regarding such deviations as genuine, the interpretation of the displacements on the basis of the Doppler effect would be condemned. One could not reasonably admit the various absorption centers present in a gas-current at a certain level to have different proper velocities of outflow from the spot vortex.

THE INTERPRETATION BASED ON ANOMALOUS DISPERSION

As would appear from the preceding discussion of the radial-motion hypothesis, it is not superfluous to look for other ways of explaining the relative displacements of the Fraunhofer lines at the limb- and center-edges of the penumbrae of eccentrically located spots.

In a previous paper[1] I suggested an explanation of the sun's edge and of the general distribution of the brightness on the solar disk, assuming the non-existence of a photosphere in the sense of the surface of a body or of a layer of clouds. The term "photosphere" is preserved; but in the new interpretation it only means a mathematical sphere constructed round the sun's center and having for its radius the distance between the center and the apparent edge of the disk. The gaseous condition of the solar atmosphere continues below the photosphere without any abrupt change in the physical or chemical properties of the mixture. The increase of the mean density and the variation of the mean composition are progressive.

Our sun-spot hypothesis advanced in 1909[2] considered the distribution of the light in a spot as chiefly produced by the refraction which photospheric light suffers when traversing a region where the optical density passes through a minimum (e.g., a solar vortex).

It has been doubted whether in the solar *atmosphere* differences of density, sufficient for imparting to the rays the important deviations required by the theory, really could exist. This objection will disappear if the new interpretation of the photosphere be accepted, because the present point of view permits of locating that region of minimum density somewhere below the photospheric level, in layers where sufficient gradients of optical density are sure to be found.

A rough estimate of the values which optical density gradients must have in order to produce an observable incurvation of average rays (for which the medium possesses small refracting power) has been given in a previous paper.[3] It should be remembered that in the present paper we are dealing with R-light and V-light,[4]

[1] *Astrophysical Journal*, **38**, 129, 1913.

[2] *Proc. Roy. Acad. Amst.*, **12**, 266, 1909; *Physikalische Zeitschrift*, **11**, 56, 1910.

[3] *Astrophysical Journal*, **38**, 135, 1913.

[4] Defined as waves lying respectively on the red-facing and the violet-facing sides of absorption lines and very near to them; cf. *Proc. Roy. Acad. Amst.*, **12**, 275, 1909; or *Physikalische Zeitschrift*, **11**, 63, 1910.

that is, with waves generally more strongly refracted than the average light of the spectrum.

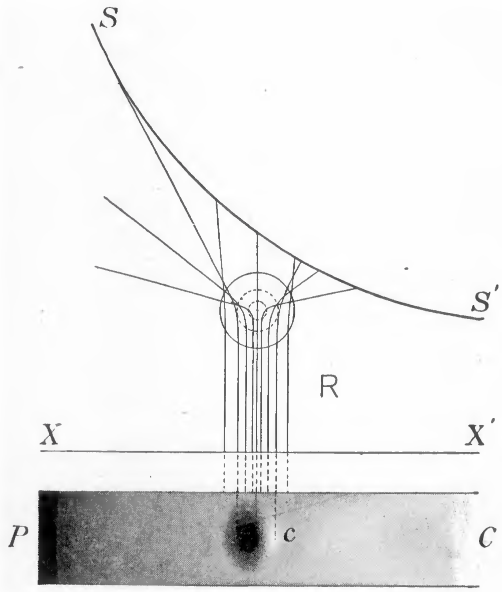


FIG. 1

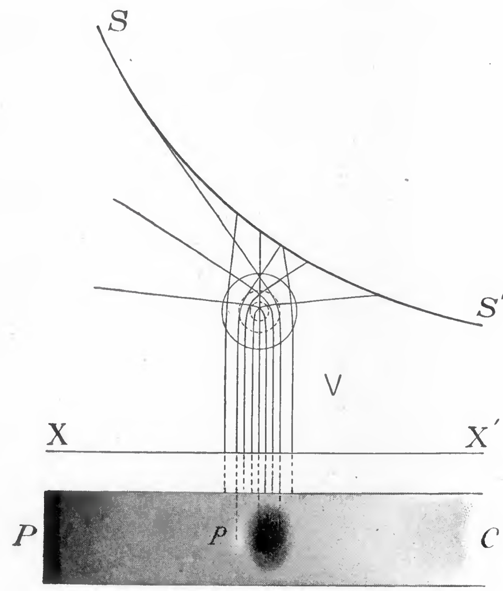


FIG. 2

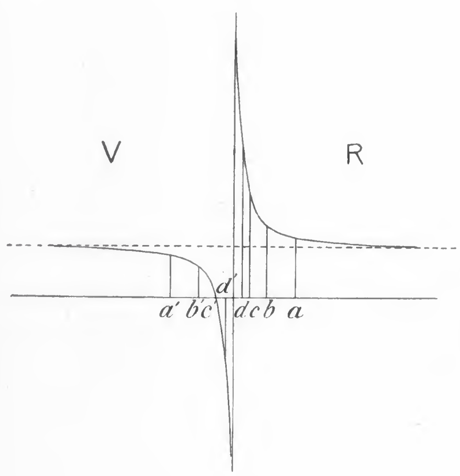


FIG. 3

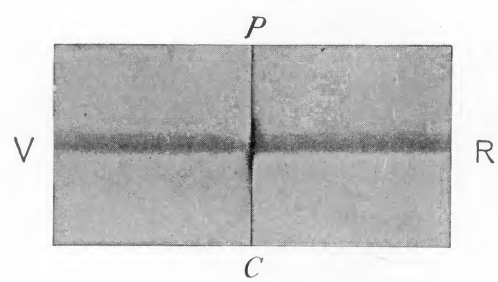


FIG. 4

The influence of an eccentrically located density minimum on the course of R-light and V-light, and the resulting effect on the spectrum, may be illustrated by means of Figs. 1, 2, 3, and 4. These are taken from the above-mentioned publication of 1909, to which I refer for a more complete explanation of the purely *schematic* case represented by them.[1] It should be noted that the drawings were only intended to bring out the essential feature of the effect of anomalous refraction in an ideal depression. In a real spot the conditions are of course far more complicated; the shape of the depression will not be spherical as assumed, and irregular gradients superposed upon the systematic gradients of the vortex region will especially influence the course of the most refrangible rays, thus confusing the schematic results for the central parts of strong lines. But provisionally abstracting from details—to which we shall revert farther on—we see that anomalous refraction causes just the kind of wryness observed with all the lines of the spot spectrum, except with a few very strong lines that correspond to prominent chromospheric lines. A discussion of the behavior of those 13 exceptional lines of the table must be postponed; in this section we confine our attention to the normal case of the 493 lines.

Besides explaining the general character of the displacements in question, the anomalous-dispersion theory should account for the following quantitative results of the observations:

1. The *mean* displacements calculated for each intensity class decrease with increasing line intensity. (For explaining this rule St. John had to introduce his new hypothesis connecting line intensity with level.)

2. Large deviations from the mean values occur in every intensity class. (St. John does not consider such deviations as purely accidental, for he bases on them various conclusions on relative levels of different elements. But if the large residuals often found when deducting the mean from the individual displacements, for lines of one element and one intensity, are real, this

[1] Some experiments on the refraction of light in whirling gases were shown on the occasion of the fifth meeting of the Solar Union in August, 1913, at Bonn, and are described in *Physikalische Zeitschrift*, 15, 48, 1913. As remarked in a footnote of that paper, our recent interpretation of the photosphere made it possible to improve the sun-spot hypothesis of 1909 by admitting that the spot vortex or region of minimum density might be located *below* the photospheric level. The arc SS' of our figures, therefore, does not now represent a part of the photosphere, but a part of a lower level.

would seem to present, as already remarked, an insuperable difficulty for the interpretation of the phenomenon as a radial-motion effect.)

3. The displacements increase with the wave-length, but not proportionally. The observations do not indicate a simple law, and the rate of increase seems to vary differently for different intensity classes. (It is impossible to explain these facts on the basis of the Doppler effect without calling in additional hypotheses in order to account for the large deviations from proportionality with wave-length.)

From the point of view of the anomalous-dispersion theory it is at once clear that there must be a direct connection between the intensity of the lines and the magnitude of their displacements in spots, as both phenomena depend on the "dispersion bands" enveloping the absorption lines. It would be rash and erroneous, however, to conclude that strong anomalous dispersion, because it produces Fraunhofer lines of great intensity, must also give rise to large relative displacements in the spot spectrum. Indeed, the reverse is true. This will come out clearly in the course of the discussion; but before settling this point we had better first consider the possible cause of the second rule: the great disparity of the displacements.

Disparity of the displacements. Mutual influence of Fraunhofer lines.—If the displacement of a certain line A depends on the refracting power of the medium for the adjacent waves, it must be influenced by the presence of a strong neighboring line B. Let us discuss the nature of that influence.

Let n_0 be the value which the refractive index would have in the part of the spectrum under observation if this were free from absorption lines, and suppose n_0 to be >1. The effect of a line B (Fig. 5) is to reduce the indices on its violet side and to raise them on its red side, as indicated by the partly broken curves. The line A, if isolated, would produce its own anomaly in the dispersion-curve as shown in A_1. If A were situated near B, in one of the positions A_2 or A_3, that anomaly would have a somewhat different shape in consequence of its being superposed upon one of the branches of the dispersion-curve due to B. The refracting properties of the medium, being determined by the values of $n-1$, will be different in the three cases represented by A_1, A_2, and A_3.

Only those waves for which the absolute values of $\pm(n-1)$ exceed a certain minimum value will become sufficiently curved in the outer parts of the vortex region to give rise to sensible refraction effects in the spectrum of the penumbra. This is indicated in the figure by means of the two broken lines drawn at equal distances above and below the line $n=1$. We may assume that only the

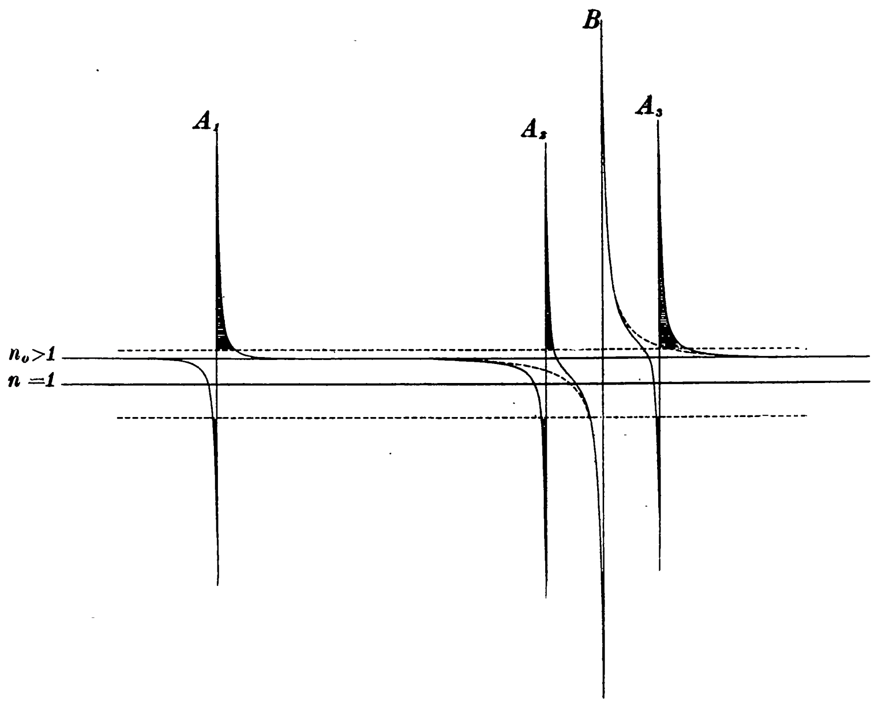


FIG. 5.—Mutual influence of Fraunhofer lines

parts of the dispersion-curve lying outside the zone between these broken lines are material to the formation of the dispersion bands enveloping the absorption lines of the penumbral spectrum. The R-light corresponding to the shaded area above the zone is responsible for the displacements toward the red observed at the peripheral edge of the penumbra; the V-light corresponding to the shaded area below the zone causes the displacements toward the violet at the central edge.

Now comparing for the lines A_1, A_2, and A_3 the horizontal distances between the "centers of gravity"[1] of their R-area and V-area, we at once realize that A_2 will show a smaller displacement than A_1, and A_3 a greater displacement than A_1; but it is also evident from the figure that the difference between the cases A_3 and A_1 is not so marked as that between A_2 and A_1.

This deduction from the theory can be put to the test by means of St. John's observations.

After having marked out on Higgs's atlas of the normal solar spectrum the 506 lines of Table I, I selected *all* cases in which a measured line A of intensity 3 or lower was on the *violet* side of a stronger line B (generally of intensity 4 or higher) at a distance of about 0.5 A or less. A few cases in which the line A had another strong companion B' equally near but on the other side were of course discarded. Forty-three pairs answering the conditions were found; they are united in the first column of Table IV. The wave-lengths of lines B not appearing in St. John's Table I were read on Higgs's atlas. Most of these lines could be identified with lines occurring in Mitchell's table of wave-lengths of the chromosphere.[2] In the second and third columns of our Table IV are the elements and intensities; the elements in brackets are taken from Mitchell's table. The fourth column contains the corrected values Δ' of the observed relative displacements as given by St. John.[3] In the fifth column are indicated "normal" values of the displacements. These were obtained from the data appearing in the upper section of Table II after having supplemented them by inserting between the numbers for violet and yellow-red those given for mean λ 4992 in Table III. Thus, on the basis of the two rules found by St. John that connect the displacements with line intensity and with wave-length, it was possible to indicate a "normal" displacement peculiar

[1] The term "center of gravity" is used for convenience' sake. Properly speaking, the estimated location of the lines will of course depend on considerations somewhat different from those involved in the determination of the center of gravity of the said area.

[2] *Astrophysical Journal*, **38**, 407, 1913.

[3] I have not used the values Δ' reduced to λ 5000, because that reduction derived its direct meaning from the assumption that the relative displacements are due to the Doppler effect.

TABLE IV

THE *Decrease* OF THE AMOUNT OF THE EVERSHED EFFECT IN THE SPECTRUM OF ECCENTRICALLY LOCATED SUN-SPOTS, OBSERVED WITH THE *Violet*-AND-WEAKER MEMBERS OF PAIRS OF LINES.

λ	Element	Intensity	Observed Displacement Δ′	Normal Displacement	Difference	Remarks
3649.137	Cr	1	0.014	0.022	−0.008	
3649.4	....	5	....	....	....	
3662.096	Ni	3	.015	.015	.000	
3662.38	(Ti)	5	....	....	....	
3686.926	Cr	1	.016	.022	− .006	
3687.2	....	3	....	....	....	
3687.234	Fe	3	.010	.015	− .005	
3687.610	Fe	6	....	....	....	
3688.210	V	1	.018	.022	− .004	
3688.5	....	4	....	....	....	
3690.599	Fe	2	.017	.020	− .003	
3690.8	....	3	....	....	....	
3707.702	Ti	2	.013	.020	− .007	
3708.07	(Fe)	6	....	....	....	
3708.964	Co	1	.015	.022	− .007	
3709.389	Fe	6	....	....	....	
3895.119	Co	3	.012	.015	− .003	
blend	....	4?	....	....	....	
3895.583	Mn	3	.008	.015	− .007	
3895.803	Fe	7	....	....	....	
3898.032	Fe	3	.007	.015	− .008	
3898.2	....	4	....	....	....	
3899.171	Fe	3	.013	.015	− .002	
3899.21	(V–Fe)	3	....	....	....	
3906.438	Co	2	.010	.020	− .010	
3906.628	Fe	10	....	....	....	
3913.123	Ni	2	.016	.020	− .004	
3913.609	Ti	5	....	....	....	
3916.879	Fe	5	.009	.014	− .005	
3917.32	(Fe)	6	....	....	....	
3947.522	?	2	.014	.021	− .007	
3947.675	Fe	4	....	....	....	
3956.603	Fe	4	.010	.014	− .004	
3956.879	Fe	6	....	....	....	
3958.073	Co	2	.018	.022	− .004	
3958.36	(Zr–Ti)	4	....	....	....	
3962.995	Ti	3	.012	.016	− .004	
3963.2	....	4	....	....	....	
3995.899	La	1	.014	.023	− .009	
3996.14	....	3	....	....	....	
3997.115	Fe	2	.019	.022	− .003	
3997.547	Fe	4	....	....	....	
4035.752	Co	2	.016	.022	− .006	
4035.883	Mn	4	....	....	....	
4109.609	Nd	1	.016	.024	− .008	
4109.95	....	4	....	....	....	
4132.100	V	2	0.011	0.022	−0.011	
4132.235	Fe	10	....	....	....	

TABLE IV—*Continued*

λ	Element	Intensity	Observed Displacement Δ′	Normal Displacement	Difference	Remarks
4133.755	Fe	2	0.022	0.022	0.000	
4133.95	(Fe–Ce)	4	....	....	....	
4149.360	Zr	2	.016	.022	− .006	
4149.5	....	4	....	....	....	
4216.136	CN	1	.022	.024	− .002	
4216.35	(Fe)	4	....	....	....	
4233.328	Mn–Fe	4	.017	.017	.000	
4233.772	Fe	6	....	....	....	
4271.325	Fe	6	.009	.014	− .005	Distance >0.6 A
4271.934	Fe	15	....	....	....	
4274.746	Ti	2	.016	.023	− .007	
4274.958	Cr	7	....	....	....	
4289.525	Ca	4	.015	.019	− .004	
4289.885	Cr	5	....	....	....	
4294.936	Zr	2	.018	.023	− .005	
4295.29	Dy	6	....	....	....	
4302.353	Fe	2	.019	.023	− .004	
4302.692	Ca	4	....	....	....	
4315.138	Ti	3	.010	.021	− .011	
4315.262	Fe	4	....	....	....	
4408.364	V	2	.027	.024	+ .003	Influenced by λ 4407.8, int. 6
4408.54	(V)	4	....	....	....	
5168.832	Ni	1	.026	.028	− .002	
5169.16	(Fe)	7	....	....	....	
5188.863	Ti	2	.015	.026	− .011	
5189.0	....	3	....	....	....	
5226.707	Ti	2	.020	.026	− .006	
5227.0	....	4	....	....	....	
5250.385	Fe	2	.028	.027	+ .001	
5250.82	(Fe)	3	....	....	....	
5298.194	Cr	1	.021	.029	− .008	
5298.455	Cr	4	....	....	....	
5598.524	Fe	1	.019	.030	− .011	
5598.711	Ca	4	....	....	....	
5615.520	Fe	2	.025	.027	− .002	
5615.877	Fe	6	....	....	....	
5624.245	Fe	1	0.027	0.031	−0.004	
5624.77	(Fe)	4	....	....	....	
					Mean diff. −0.0051	

to the spectral region and the intensity of each measured line. With these normal values the observed values had to be compared.

As expected, the differences shown in the sixth column are negative. There is one distinct exception: λ 4408.364, for which the difference is +0.003. This line, however, has also a companion *B′* on the violet side (λ 4407.8 of intensity 6) that would work the opposite way, so that perhaps the case ought to have been discarded although the distance between A and B' is a little greater than 0.5 A. On the average, the measured displacements of these forty-three violet members of pairs are as much as 0.0051 A smaller than the normal values. This result is in perfect harmony with our assumption that the displacements depend on the refracting power of the medium.

Additional evidence is obtained from Table V, which contains data similar to those of Table IV, but now relative to thirty-nine pairs, the weaker line A of which is on the *red* side of the stronger line B. In these cases the observed displacements of A should generally exceed the normal values, but the effect is expected to be less conspicuous than the reduction of the displacements on the violet side of lines B.

As a matter of fact, the differences in the sixth column are for the greater part positive. And examining on Higgs's atlas the environment of the 12 lines that gave negative deviations from the normal displacements, we find some cases where an additional strong neighboring line B' on the wrong side may be responsible for the discrepancy (e.g., λ 3947.918 might be influenced by λ 3948.25 of intensity 5, and λ 3949.039 by λ 3949.25 of intensity 3). The average increase of the relative displacements above their normal values, attributed to the violet companions of our thirty-nine lines, amounts to nearly +0.0015 A. Omitting the dubious cases we should have found the mean residual +0.0019 A.

It must be granted that the difference between the absolute values of the negative mean residual 0.0051 and the positive mean residual 0.0015 appears too great to be entirely accounted for by the inequality of the configuration of the shaded areas on the two sides of B, as represented in Fig. 5. The difference, however, may be partly due to a systematic observational error; for it is not improbable that the proximity of a strong line B causes the displacements of lines A to be underestimated. Allowing for this error—which of course would have the same sign on either side of B—we must reduce the observed negative and enlarge the positive mean residual by the same amount. Their absolute values thus

TABLE V

THE *Increase* OF THE AMOUNT OF THE EVERSHED EFFECT IN THE SPECTRUM OF ECCENTRICALLY LOCATED SUN-SPOTS, OBSERVED WITH THE *Red*-AND-WEAKER MEMBERS OF PAIRS OF LINES

λ	Element	Intensity	Observed Displacement Δ′	Normal Displacement	Difference	Remarks
3694.24	(Fe–Ni)	8	....	....	....	
3694.344	Yt	3	0.020	0.015	+0.005	
3694.344	Yt	3	....	....	....	
3694.576	La	1	.027	.022	+ .005	
3704.603	Fe	4	....	....	....	
3704.840	V	1	.016	.022	− .006	
3706.24	(Mn–Ti–Ca)	7	....	....	....	
3706.363	Fe	3	.017	.015	+ .002	
3711.364	Fe	4	....	....	....	
3711.552	Fe	3	.015	.015	.000	
3898.2	....	4	....	....	....	
3898.531	Mn	2	.014	.020	− .006	
3947.675	Fe	4	....	....	....	
3947.918	Ti	2	.013	.021	− .008	Influenced by λ 3948.25, int. 5
3948.925	Fe	4	....	....	....	
3949.039	Ca	1	.018	.022	− .004	Influenced by λ 3949.25, int. 3
3950.102	Fe	15(?)	....	....	....	
3950.497	Y	5	.013	.014	− .001	
3984.17	(Fe–Mn)	6	....	....	....	
3984.294	Mn	2	.021	.020	+ .001	
3989.912	Ti	4	....	....	....	
3990.011	Fe	3	.012	.015	− .003	
4018.25	(Mn)	7	....	....	....	
4018.420	Fe	3	.022	.015	+ .007	
4078.49	?	4	....	....	....	
4078.631	Ti	3	.017	.016	+ .001	
4079.4	....	5	....	....	....	
4079.570	Mn	3	.018	.016	+ .002	
4134.54	(V–Fe)	6	....	....	....	
4134.840	Fe	5	.014	.014	.000	
4161.68	(Ti)	5	....	....	....	
4161.961	Sr	1	.025	.024	+ .001	
4184.32	(Ti–Gd)	5	....	....	....	
4184.472	Ti	2	.022	.022	.000	
4196.35	?	4	....	....	....	
4196.699	La	2	.024	.022	+ .002	
4236.112	Fe	8	....	....	....	
4236.429	Ni	1	.024	.024	.000	
4240.64	(Zr–Ce–Fe)	4	....	....	....	
4240.872	Cr	1	.022	.024	− .002	
4338.084	Ti	4	....	....	....	
4338.430	Fe	1	.025	.024	+ .001	
4637.685	Fe	5	....	....	....	
4638.193	Fe	4	.027	.021	+ .006	
4667.626	Fe	4	....	....	....	
4667.768	Ti	3	.027	.023	+ .004	
4679.027	Fe	6	....	....	....	
4679.409	Ni	2	0.037	0.024	+0.013	

TABLE V—*Continued*

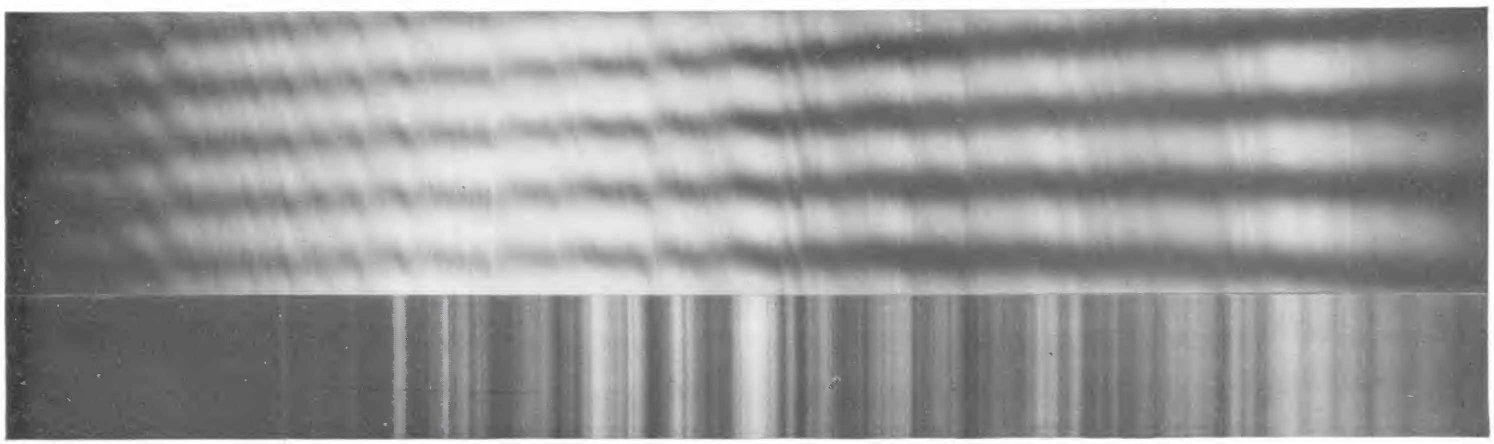
λ	Element	Intensity	Observed Displacement Δ′	Normal Displacement	Difference	Remarks
4703.177	Mg	10	....	....	....	
4703.994	Ni	3	0.035	0.023	+0.012	Distance >0.6 A
4731.65	(Fe)	4	....	....	....	
4731.984	Ni	1	.030	.026	+ .004	
4736.96	(Fe)	6	....	....	....	
4737.540	Cr	2	.034	.024	+ .010	
4762.567	Mn	5	....	....	....	
4762.820	Ni	1	.039	.026	+ .013	
5129.42	(Ti–Ni)	5	....	....	....	
5129.546	Ni	2	.026	.024	+ .002	
5129.546	Ni	2	....	....	....	
5129.805	Fe	1	.033	.028	+ .005	
5131.642	(Fe–C)	3	....	....	....	
5131.942	Ni	1	.029	.028	+ .001	
5152.087	(Fe–C)	3	....	....	....	
5152.361	Ti	0	.031	.031	.000	
5192.523	(Fe–Nd)	5	....	....	....	
5193.139	Ti	2	.021	.026	− .005	Distance >0.6 A
5283.802	(Fe)	6	....	....	....	
5284.281	Ti	1	.026	.028	− .002	
5298.455	Cr	4	....	....	....	
5298.672	Ti	1	.022	.028	− .006	
5349.652	Ca	4	....	....	....	
5349.928	Fe	1	.027	.028	− .001	
5857.674	Ca	8	....	....	....	
5857.976	Ni	3	.030	.027	+ .003	
5953.0	(Ti–Fe)	5	....	....	....	
5953.386	Ti	1	.038	.032	+ .006	
6400.217	Fe	8	....	....	....	
6400.528	Fe	2	0.026	0.031	−0.005	
					Mean diff. +0.00146	

approach each other, whereas the characteristic difference between the cases A_2 and A_3 remains unaffected.

Taken all in all, the evidence is very strong in favor of the view that the displacements here considered are entirely due to anomalous refraction.

The interpretation of the phenomena on this basis easily accounts for the great and frequent deviations of individual displacements from the normal values, and thus increases our confidence in the accuracy of St. John's measurements. Indeed, if we take it for granted that every Fraunhofer line influences the refractive index of the gaseous mixture in a way similar to that in

PLATE I



Record obtained with a Jamin interferential refractometer and a Hilger spectrograph, showing how the refractive index of a selectively absorbing medium (NO_2) fluctuates along the spectrum under the influence of the absorption lines.

which our lines B have been proved to do, the value of n_0 must oscillate sensibly along the whole spectrum, especially in regions where the lines are crowded. The refracting power of the solar atmosphere would then be analogous to that of a terrestrial gas giving an absorption spectrum with a great number of lines. Plate I is intended to illustrate such a case. It shows the refracting power of *nitrogen peroxide* as recorded by means of a Jamin interferential refractometer and a small Hilger spectrograph.[1] Both the rapid variations of the refractive index near prominent lines, and the gradual fluctuations of the mean index caused by groups of lines are well shown. Now, from our Fig. 5 (p. 12) it is clear that for a line of given intensity the magnitude of the relative displacement in the spot spectrum will depend on the value which n_0 has in the part of the spectrum under consideration, as well as on the presence of direct neighboring lines. Hence one cannot be astonished at finding very unequal displacements with lines of the same intensity, the same element, and about the same region of the spectrum. This is an important inference, in respect to which our point of view has the advantage over the radial-motion hypothesis.

Unless some other plausible explanation of this peculiar mutual influence of neighboring lines on the magnitude of their displacements be found, we are forced to consider the foregoing results as a direct proof of the efficiency of anomalous dispersion in producing solar phenomena.

Displacements and line intensity.—Our next aim must be to explain the fact that, on the average, the displacements decrease with the increase of line intensity.

This problem brings us in contact with a characteristic feature of our theory that has given rise to some misapprehension and opposition.

Line displacements caused by Doppler effect, Humphreys effect, and Zeeman effect will increase in proportion as the velocity, the pressure, and the strength of the magnetic field increase; but the analogous inference that solar line displacements caused by

[1] *Proc. Roy. Acad. Amsterdam*, 13, 1088, 1911; *Zeitschrift für wissenschaftliche Photographie*, 10, 62, 1911.

anomalous dispersion should always increase in proportion as the degree of anomalous dispersion in the sun increases, or that they should even be proportional to the refraction effects observed with the corresponding lines in the laboratory, is entirely erroneous.

This, of course, does not involve the assertion that results on anomalous dispersion obtained from terrestrial sources would be without any value for the interpretation of solar phenomena. On the contrary, in the theory advanced, as in any other interpreting system, observation aided by experimental research is the only reliable basis; but in criticizing the conclusions of the rival theories it should be noted that the relations of anomalous dispersion are very different from those of other causes of line displacements, and require special study.

In order to compare the refraction effects associated with weak and with strong lines we once more refer to the schematic Figs. 1–4 on p. 9, and to their interpretation given in the paper mentioned in the footnote of p. 10. The case represented is an ideal one, not only because we gave the depression a spherical shape, but also on account of the assumed smoothness of the gradients.

We shall now consider the effect of slight irregularities of optical density superposed upon the systematic gradients due to the vortex.

Waves for which $\pm(n-1)$ is not very much greater than n_0-1 (n_0 being the mean refractive index for the spectral region under consideration) will essentially behave in accordance with the ideal case, although their paths will appear somewhat sinuous on account of the small fluctuations of the density. Such are the conditions obtaining with the R-light and V-light of lines of low intensity. The aspect of those lines will therefore nearly correspond to the shape represented in Fig. 4. If a wave-length belonging to the R-light of a weak line could be isolated with the spectroheliograph, the solar image thus obtained would show the spot displaced toward the limb; similarly a wave-length belonging to the V-light would show the spot displaced toward the center of the disk. This involves that in the spectrum of the limb-edge the intensity of the dark line falls off sharply on the violet side, progressively on the red side, and just the reverse in the spectrum of the center-edge of the spot.

The following weak lines, visible on Fig. 1 of the plate[1] of St. John's first paper, show this characteristic of our schematic line (Fig. 4, p. 9, where the effect is exaggerated) unmistakably: $\lambda\lambda$ 4750.1, 4751.28, 4764.5, 4764.72, 4768.85, 4776.26, 4778.4, 4781.9.

The measured values of the displacements of lines of this kind are determined by the difference of wave-length between the "centers of gravity" of their R-light and V-light areas, in so far as the width of the true absorption line, common to both edges of the penumbra, may be neglected.

The peculiar shape which these lines of very low intensity show in the spot spectrum when observed with radial slit corroborates the fundamental hypothesis of our solar theory, viz., that the width of Fraunhofer lines is in the main an effect of anomalous dispersion.

Proceeding to the case of a stronger line, we are concerned with waves for which $\pm(n-1)$ has such high values that even the lesser, parasitical density gradients make those rays deviate very sensibly. The rays will then follow winding paths entirely different from the smooth lines of the drawings, Figs. 1 and 2, p. 9. Thus, e.g., a ray of V-light emerging from the peripheral part of the penumbra, which if only moderately refracted would have carried much energy (according to Fig. 2), will now on account of its frequent curving possibly take the energy from a less favorable direction, and will at all events have suffered more loss by scattering, both molecular and refractional, than have waves for which $\pm(n-1)$ is smaller.

We may also consider the matter thus: very strongly refrangible rays are not so much influenced by the large-scale density configuration of the vortex region. In fact, such rays are refracted by the irregular gradients outside as well as inside the vortex regions; and although equal positive and negative values of $n-1$ determine opposite incurvations, the paths are everywhere so twisted throughout the whole layer corresponding to the levels where sun-spots occur, that the combined effects of those waves blend into a

[1] Cf. *Mt. Wilson Contr.*, No. 69, Plate XXIV; *Astrophysical Journal*, **37**, 324, 1913, Plate XII.

vague, fine-grained structure, and the systematic spot-gradients are scarcely indicated by them.[1]

In the spectrum of the spot, therefore, the strongly refracted waves will not in general produce any marked asymmetrical phenomenon. By their winding and scattering amid the lesser density fluctuations they get possibly still more weakened inside than outside the vortex region, and thus make the line appear strengthened and widened,[2] but nearly equally so on both edges of spot and line, the average effect being almost the same for R-light and V-light. Waves a little farther from the core of the line, however, are less refracted and behave according to the scheme that holds good for weak lines; hence the shading of the line will be broader on the red than on the violet side in the peripheral penumbra, and broader on the violet than on the red side in the penumbra directed toward the center of the disk. This makes it appear that the line is shifted bodily. When the relative displacement is being measured, the strong central part which the lines of both spot-edges have in common will preponderate in the determination of the "centers of gravity"; in this way the displacement will come out smaller than with lines of low intensity. This diminution of the distance between the estimated centers, progressive with increasing line intensity, explains the law discovered by St. John.

Displacements and wave-length.—We shall now discuss from our point of view the connection that seems to exist between displacements and wave-length.

Together with the data given in Tables II and III the contents of Table VI, graphically represented in Fig. 6, may serve to provide us with a survey of the available material.

[1] Spectroheliographic images obtained with the very centers of strong lines really do not show the spots (Deslandres); they give, however, some coarse details corresponding to higher levels, where the smoother gradients suffice to impart to those highly refrangible rays the deviations necessary for producing contrasts.

[2] The exceptionally wide lines H, K, H_α, H_β, H_γ, H_δ, and some other winged lines require special treatment, because with them very probably the middle part of the dispersion-curve uniting the minimum with the maximum will have to be taken into consideration. A discussion of the enhanced lines and those weakened in the spot spectrum must also be postponed until the completion of a laboratory investigation now in progress.

In the first column of Table VI are indicated ten regions of the spectrum, including all the observed lines; the second column contains the numbers of the lines measured in each region; in the

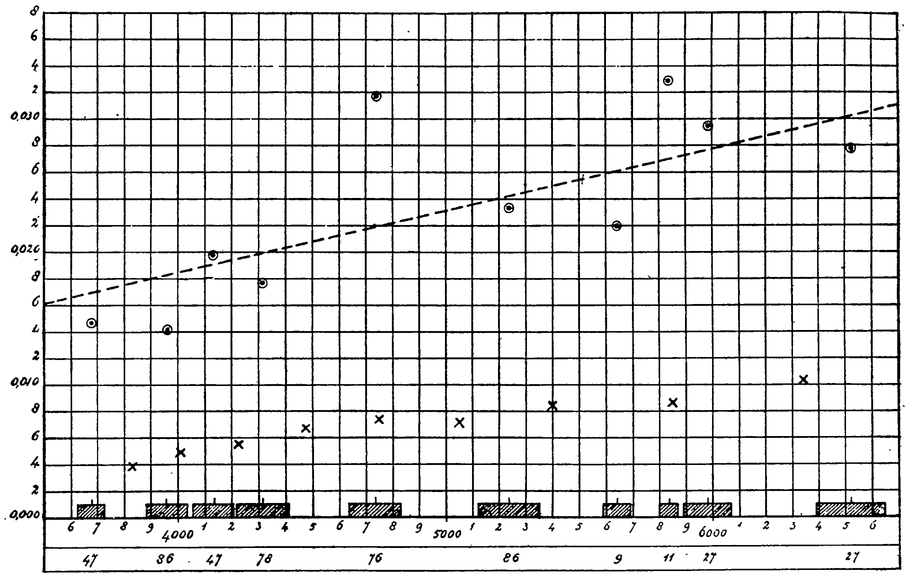


FIG. 6.—Mean displacements in successive regions of the spectrum
⊙ ⊙ ⊙ relative displacements in spot spectra (St. John)
× × × displacements at the sun's limb (Adams)

TABLE VI

DISPLACEMENTS AND WAVE-LENGTH

Region of Spectrum	Number of Lines	Mean λ	Mean Displacement
λ 3625 to 3725.........	47	3675	0.0147
3880 to 4035.........	86	3957	.0141
4055 to 4205.........	47	4130	.0197
4215 to 4410.........	78	4312	.0176
4635 to 4830.........	76	4732	.0317
5120 to 5350.........	86	5235	.0233
5590 to 5690.........	9	5640	.0219
5800 to 5870.........	11	5835	.0328
5890 to 6070.........	27	5980	.0294
6390 to 6650.........	27	6520	0.0277

third and the fourth columns are the mean wave-length and the mean displacement for each region.

Although on the average the displacements obviously increase with wave-length, the most striking feature of the table and the figure[1] is the great variety of the *mean* values along the spectrum. One cannot admit such fluctuations to be entirely accidental or due to observational errors. The important retrograde difference between the values for mean λ 4732 and mean λ 5235, e.g., far exceeds the mean error of the result of 76 and 86 observations, and must be genuine.[2] If the Doppler effect were the cause of the displacements, their variation with wave-length would be represented by the straight line shown in the figure. The great deviations from this line prevent us from considering the data as decisively in favor of the hypothesis that we are dealing with a radial motion phenomenon. We suggest under reserve the following explanation, in which the combined effects of scattering and refraction are considered.

Suppose for a moment that the irregular density gradients of the solar gases had all disappeared, only the slow radial gradient being left. We should then look down through a perfectly calm, moderately transparent medium upon an evenly luminous background. The brilliant core of the sun would be seen through a kind of haze or fog caused by molecular scattering. As the scattering coefficient varies inversely as the fourth power of the wave-length, any definite degree of fogginess would be found for violet light at a higher level than for red light. If there were self-luminous or absorbing objects in the medium, they would be visible down to greater depths with red waves than with violet waves.

Now let the density gradients reappear, and with them the sinuating of rays and the resulting irregular distribution of the light. Evidently the beams of red waves will have traveled longer distances through the sun before emerging than the beams of violet waves; at the lower levels the average density gradients

[1] The mean relative displacements in the spot spectrum are indicated by small circles. The crosses in the lower part of the figure give the mean values of the displacements of Fraunhofer lines *at the limb* for successive regions of the spectrum, as deduced from measurements made by Adams.

[2] It is worth noticing that this anomaly occurs at the same place in the spectrum where the curve representing the means of Adams' measurements of limb displacements as a function of wave-length also sinuates (cf. Fig. 6), and where H. C. Vogel's well known table of spectrophotometric observations on the distribution of various kinds of light on the solar disk shows a similar anomaly. We do not venture to explain these remarkable coincidences as yet, although the anomalous-dispersion theory indicates connective points.

probably are steeper; red light therefore has in general more opportunities to get strongly deviated, and thus to produce contrasts, than violet light. This may account for the general tendency of the displacements to increase with increasing wave-length.

As to the fluctuations of the mean displacements along the spectrum, it seems possible to make the oscillating values of $n_0 - 1$ responsible for them, in the manner already discussed on p. 19.

ON ST. JOHN'S APPRECIATION OF ANOMALOUS DISPERSION AS A POSSIBLE CAUSE OF THE RELATIVE DISPLACEMENTS

Although the preceding pages implicitly contain a reply to the greater part of St. John's critical remarks on anomalous dispersion, it would seem proper still to discuss briefly his principal objections seriatim.

In judging of the degree of correspondence between the figure illustrating the way in which anomalous dispersion acts in producing the shifts (Fig. 4, p. 9) and the aspect of the lines found on the plates, St. John confined his attention to the stronger lines. Our schematic figure, however, is not directly applicable to strong lines for the reasons amply discussed on p. 21. In the case of weak lines the correspondence appears to be quite satisfactory.

Of the three facts mentioned by St. John as requiring explanation from the point of view of anomalous dispersion, two have been explained in this paper, viz., the variation of displacement with wave-length, and the variation with the intensity of the lines. The fact that a few lines (corresponding to prominent chromospheric lines) are displaced in the opposite direction has provisionally been left out of consideration in view of a special research now in progress. On the other hand, a fourth and very marked fact not explained by St. John's theory, viz., the large deviations of individual displacements from the means for each intensity class and spectral region, is shown to be in harmony with our interpretation on the basis of anomalous dispersion.

In a note on the interpretation of spectroheliograph results and of line-shifts[1] I explained why Mr. Adams, when comparing

[1] *Astrophysical Journal*, 31, 428, 1910.

certain laboratory results on anomalous dispersion with the displacements of Fraunhofer lines at the limb,[1] failed to find any clear relationship between the two phenomena. Mr. St. John criticizes this explanation. He quotes from my paper:

That a simple comparison of Geisler's observations on anomalous dispersion of metallic vapors in the arc with displacements at the limb—as given by Adams on page 28—could not possibly serve the purpose of finding such a relationship is evident. . . . .

Now, this was only a fraction of a sentence; the continuation of it runs thus:

for the amount of that part of the displacement which is due to anomalous dispersion is determined by the degree of asymmetry of the Fraunhofer line under consideration; and this asymmetry is not a mere property of the corresponding element itself, revealable in laboratory experiments, but depends on the concentration with which that element is represented in the solar atmosphere.

But instead of completing the quotation by adding these explanatory lines, St. John comments as follows:[2]

In view of the consideration that the basis of all astrophysical investigations rests upon the fundamental postulate that direct comparison is possible between the spectrum results obtained from terrestrial sources and the behavior of the spectrum lines in solar and stellar spectra, the first statement in the quotation is somewhat remarkable.

I am sure Mr. St. John would not have suggested to his readers such a bad opinion of my working method if he had realized the meaning of the part of my argument which he represented by an ellipsis. Indeed, from the point of view that Fraunhofer lines are dispersion bands, their asymmetry is due to the fact that, for the narrow region of wave-length surrounding each separate line, $n_0 - 1$ generally differs from zero (n_0 being determined by the composition of the solar gaseous mixture). The degree of asymmetry depends on both n_0 and the anomaly produced by the line itself.[3] As in Geisler's experiments the solar values of n_0 did not enter, nor anything analogous to them, the magnitude of the displacements of

[1] *Astrophysical Journal*, **31**, 57, 1910.

[2] *Mt. Wilson Contr.*, No. 74, p. 43.

[3] *Proc. Roy. Acad. Amsterdam*, **12**, 281, 1909; *Physikalische Zeitschrift*, **11**, 68, 1910.

the Fraunhofer lines at the limb bears no relation at all to the results of those experiments. This assertion does not imply any disregard of the necessity of testing theories by experimental research wherever possible, provided that the test be based on sound reasoning.

St. John's next criticism bears on the following statement which he quotes from the same paper: "A peculiar feature of our explanation is that both very strong and very weak anomalous dispersion make the displacements small, whereas intermediate values give larger displacements."

We were here concerned with displacements at the limb. Relative displacements at opposite edges of the spot spectrum have an entirely different origin. It is clear, indeed, that if a Fraunhofer line happened to be perfectly symmetrical ($n_0 - 1 = 0$) in the spectrum of the mean photospheric light, anomalous dispersion would not displace it at the limb, but would nevertheless produce a relative displacement at the opposite edges of the spot spectrum. The sign of $n-1$ is material to the Evershed effect, but almost immaterial to the Adams effect.

This fundamental difference between the two kinds of solar displacements escaped St. John's notice. In Table XXII (*Contribution No. 74*, p. 43) he uses some of his observations on spot lines in order to disprove my contention regarding limb lines! The same confusion runs through pp. 44 and 45 of the paper; this is the cause of St. John's finding so many discrepancies between the results of his observations and what he wrongly believes to be requirements of the dispersion theory.

I can easily show, using Adams' measurements of the displacements of the Fraunhofer lines at the sun's limb,[1] that the above-quoted deduction from the anomalous-dispersion theory is in perfect harmony with the facts.

Adams himself considers pressure as the effective agent in producing these displacements; it therefore did not occur to him to classify the shifts according to line intensity. Now accomplishing this classification, we obtain the synopsis given in Table VII.

[1] Adams, *Mt. Wilson Contr.*, No. 43; *Astrophysical Journal*, 31, 30, 1910.

The result is very striking; the shifts are greatest for lines of intensity 5, 6, and 7, and decrease progressively for the lower as well as for the higher intensities. This is exactly what the theory requires on the view that the intensity of Fraunhofer lines is chiefly determined by anomalous dispersion, and that their apparent displacements toward the red are simply due to the inequality of the average refraction suffered by the R-light and the V-light of

TABLE VII

SYNOPSIS OF ADAMS' MEASUREMENTS OF THE DISPLACEMENTS OF LINES AT THE LIMB, SHOWING THE MEANS FOR EACH LINE INTENSITY

	Intensity										
	0	1	2	3	4	5	6	7	8	9–12	15–40
Number of lines measured.......	7	51	99	106	71	40	41	14	12	11	15
Mean displacement (unit=0.001 A)	3.6	5.5	6.6	6.8	7.1	8.8	8.3	8.8	7.9	5.3	3.0

TABLE VIII

SYNOPSIS OF ADAMS' MEASUREMENTS OF THE DISPLACEMENTS OF LINES AT THE LIMB, SHOWING THE MEANS FOR NINE CONSECUTIVE REGIONS OF THE SPECTRUM

	Region of Spectrum								
	3740–3923	3923–4100	4100–4350	4350–4600	4600–4900	4900–5200	5200–5600	5600–6100	6100–6580
Number of lines......	52	54	70	76	38	41	54	34	50
Mean displacement (unit=0.001 A)...	3.9	4.9	5.5	6.7	7.4	7.1	8.4	8.6	10.3

each line. Indeed, the apparent displacement must then always be a *fraction* of the width of the line; it therefore decreases with line intensity. The fraction, however, will in general be smaller with wide lines than with narrow lines (for it depends on the variable proportion between $n-1$ and n_0-1), thus making the asymmetry less conspicuous in the case of the wide lines. Lines of moderate intensity therefore show the largest mean displacements. And because the value of n_0-1 fluctuates along the spectrum, especially in the vicinity of strong lines, we also conceive that in every intensity class the individual displacements may deviate widely from the mean, as they really do.

Table VIII contains the means of Adams' measurements for nine consecutive regions of the spectrum. They are plotted in the lower part of Fig. 6, and give evidence of a progressive increase with wave-length, excepting the anomaly between λ 4500 and λ 5500 already alluded to in the footnote on p. 24. This variation with the wave-length,[1] exhibited by the general shifts of the Fraunhofer lines toward the red, may perhaps be explained on the same basis as the corresponding variation observed in the case of the relative displacements in the spot spectrum (cf. p. 24). Both phenomena would seem to be due to the united influence of refraction and molecular scattering, and the refraction effects would be greater for the longer waves.[2]

Continuing the discussion of St. John's criticism, we arrive at his statement that relative displacements are sometimes observed in the spot spectrum when the slit of the spectrograph is perpendicular to the radius of the solar disk passing through the center of the umbra. It is argued that such displacements are very simply explained as Doppler effects, indicating occasional cyclonic movement, and that, on the other hand, the dispersion theory is unable to account for them. The latter inference, however, supposes the region of minimum density to have an ideally symmetrical shape. As deviations from that condition are quite probable, there is no difficulty in accounting for the occasional displacements

[1] In a paper, "Les Raies de Fraunhofer et la dispersion anomale de la lumière," published in *Le Radium*, **7**, October 1910, I suggested that the variation with wave-length here considered might be due to a general increase of n_0 with the wave-length, but I am now inclined to think that the influence of refractional scattering is more effective.

[2] A general displacement of the Fraunhofer lines toward the red, proportional to the wave-length, and amounting to about 0.010 A for λ 5000, is required by the gravitation theories of Einstein (*Annalen der Physik*, **35**, 905, 1911) and Nordström (*ibid.*, **42**, 549, 1913). Gravitation may thus contribute to the production of the observed shifts, but it certainly is not their main cause, since it does not account for the principal features of the phenomenon: the great variability of the shifts from line to line, and the marked relation between the mean shifts and the intensities of the lines.

in question on the basis of unequal refraction at opposite edges of the spot.

In the case of the *winged lines*, I had originally assumed that the core of the line was a pure absorption effect. In later publications,[1] evidently not considered by St. John in connection with the present subject, I was led to the conclusion that even the cores of those winged lines might be influenced by anomalous refraction and scattering. Probably a thorough treatment of these cases will prove to be difficult because the electronic theory of the dispersion, scattering, and absorption of light seems to require some extension in order to make it applicable to the very centers of wide lines. The subject is reserved for further investigation.

St. John's final remarks on the general question how far it seems probable that refraction and anomalous dispersion would produce any solar phenomena may be passed over, because they essentially refer to a paper, "On the Application of the Laws of Refraction in Interpreting Solar Phenomena," by Mr. Anderson.[2] At the time Mr. St. John wrote his criticism, my refutation[3] of Anderson's argument had not yet been published.

SUMMARY

1. The best established general result deduced by St. John from his measurements of the Evershed effect is that the displacements appear to vary progressively with the intensity of the lines. The regular progression of the mean values calculated for successive intensity classes pleads in favor of the general accuracy of the measurements.

2. Means taken for successive regions of the spectrum (Table VI, Fig. 6), though roughly indicating increase with wave-length, run very irregularly. Their deviations from a line representing proportionality with wave-length are too great to be attributable to accidental errors, and therefore prevent us from considering the results as decisively in favor of the hypothesis that the displacements are due to the Doppler effect.

[1] *Proc. Roy. Acad. Amsterdam*, **13**, 881 and 1263, 1911; *Physikalische Zeitschrift*, **12**, 329 and 674, 1911.

[2] *Astrophysical Journal*, **31**, 166, 1910. [3] *Ibid.*, **38**, 129, 1913.

3. St. John's hypothesis of the "Iron Scale," according to which the lines of an element are supposed to originate at a lower level as their intensity is smaller, meets with difficulties from the point of view of the physicist.

4. The insufficiency of indications of vertical motion in sun-spots is unfavorable to the hypothesis that the displacements considered are due to radial outflow of matter from spots.

5. A characteristic feature of the displacements is their great diversity of magnitude along the spectrum, even if lines of about equal intensity are considered. This peculiarity, which seems to be inexplicable on the basis of the radial-motion hypothesis, follows immediately from the anomalous-dispersion theory, because from that point of view the displacement of a line in the spot spectrum depends on (*a*) the anomaly of the dispersion-curve produced by the line considered, and (*b*) the value of n_0 which is determined by the other lines, and therefore fluctuates along the spectrum.

6. For each line intensity and spectral region a "normal displacement" can be deduced from St. John's measurements. The dispersion theory requires that the amount of the displacement of a line *A* will be sensibly influenced by a strong neighboring line *B*. On the assumption that n_0 is > 1, the influence must be such that if *B* lies on the red side of *A*, it reduces the displacement of *A* as compared with the normal value; if *B* is situated on the violet side, it must have the opposite effect, but to a lesser degree. This inference is perfectly borne out by all the evidence that can be gathered from St. John's Table I. In so far as other theories appear unable to account for this mutual influence of Fraunhofer lines, we may consider the phenomenon as directly proving the efficacy of anomalous dispersion in the sun.

7. The law connecting the Evershed effect with the intensity of the lines is in harmony with the deductions from the dispersion theory.

8. Judging from the behavior of the weakest lines (for which the optical effect of the general spot gradients is not much disturbed by the effect of superposed irregular density gradients), one gets the impression that nearly the whole width of the Fraun-

hofer lines must be due to anomalous dispersion, or that Fraunhofer lines are in the main *dispersion bands*.

9. The apparently intricate connection between displacements and wave-length seems to be explicable if we consider (*a*) that on account of molecular scattering short waves have on the average less opportunity of being refracted than long waves, and (*b*) that the value of n_0 fluctuates along the spectrum.

10. A discussion of St. John's remarks on anomalous dispersion made it necessary to expatiate on the difference in character which from the point of view of the anomalous-dispersion theory exists between the displacements of spot lines (Evershed effect), and the displacements of lines at the limb, as studied by Adams.

11. If the displacements at the limb, measured by Adams, are classified according to line intensity, and averaged, the means are found greatest for intensities 5, 6, and 7, and gradually decrease for greater as well as for smaller intensities. This law was predicted a few years ago by our theory; it will be difficult to explain it on the basis of the current interpretation of those displacements as a pressure effect.

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