Physics. — *"The Evershed effect in the spectrum of sun-spots"*. By Prof. W. H. JULIUS [1]).

(Communicated at the meeting of January 31, 1925).

A well-defined general property of Fraunhofer lines is their systematic deformation in the spot-spectrum, known as the „Evershed effect".

About 1909 EVERSHED observed [2]) that, if the slit of the spectrograph bisects a sun-spot in a direction passing through the centre of the solar disc, the lines of the spot-spectrum are systematically displaced, towards the red at the peripheral edge, towards the violet at the central edge of the spot. These displacements are small if the spot is located not far from the centre of the disc and increase as the limb is approached; their magnitude depends in a special manner upon the intensity of the lines and increases in general with the wave-length, but not proportionally. If the slit cuts the spot in other directions, similar displacements are observed, though smaller and less systematic; least when the slit is perpendicular to the radius of the disc. The hydrogen line $H\beta$ did not show the displacement, and a few other strong chromospheric lines seemed to be displaced in a direction opposite to the regular shift [3]).

It is known that EVERSHED has interpreted these phenomena as indicating motion of the absorbing gases from the umbra radially outwards, tangential to the solar surface, with velocities that increase until the outer limit of the penumbra is reached, where the motion is rather abruptly stopped.

This interpretation seemed to account fairly well for the principal characteristics of the phenemenon. It is accepted and elaborated in detail by ST. JOHN [4]) using a rich observational material collected on Mount Wilson in addition to the original Kodaikanal data. If one holds the view — taken by both observers — that the solar spectrum is a pure absorption phenomenon, it seems in fact impossible to explain the Evershed effect without having recourse to the Doppler principle; other causes of line

[1]) Soon after deliverance of the proof of this paper to Prof. JULIUS for correction for press, the Academy, to its great sorrow, received the announcement of his death on April 15, 1925.

[2]) EVERSHED, Kodaikanal Bulletin XV, 1909.

[3]) In still another respect the lines $H\alpha$ of hydrogen and H and K of calcium behave differently from the rest: their displacement begins over the photosphere, outside the penumbral region, and is not always very clearly defined, owing to the width and irregularities at the edges of the line (Transactions of the International Union for co-operation in solar Research, Vol. IV, p. 129—130). Circumstances regarding those lines evidently require separate consideration.

[4]) ST. JOHN, Contrib. Mt. Wilson Obs. N⁰. 69 and 74; Astroph. Journ. **37**, 322, **38**, 341, 1913.

displacement, like pressure, electric or magnetic fields, cannot in any satisfactory way be made responsible for the peculiarities of the phenomenon.

But now it had to be ascertained how far the necessary consequences of that Doppler explanation would prove compatible with the results of further observations, for instance with the fact that over spot umbrae the displacements are very small and uncertain in direction, nay indicating descent in the majority of cases. That serious difficulties are here encountered, I believe to have sufficiently shown on a former occasion [1]), to justify the attempt to give due attention to an entirely different interpretation of the phenomenon.

It is indeed not necessary to suppose that the darkness of Fraunhofer lines is caused by absorption alone. We may keep in view the possibility that in the solar spectrum we are dealing with *dispersion lines* [2]), in which the distribution of the light is governed by the sinuosity of rays in a medium, the optical density of which varies very irregularly in general — but rather systematically in the regions of sun-spots.

On the basis of this hypothesis too an interpretation of the Evershed effect, accounting for its most characteristic features, could be given. As a substitute for the dynamical conception of the spot, with its permanent hurricanes of many kilometers per second wind velocity — required by the absorption theory — the dispersion hypothesis introduces a rather statical conception, in which differences of density and composition determine the optical phenomena, and motion may be much slower [3]).

After the ample observations communicated by ST. JOHN in the years 1913—1915 not many new data on the Evershed effect have appeared; only one important article, published by EVERSHED himself in *Kodaikanal*

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[1]) JULIUS, Astroph. Journ. **40**, 1, 1914; **43**, 43, 1916.

[2]) In support of this theory of the solar spectrum we call to mind the following results of recent inquiry: 1. The new ideas on atomic structure are also leading to the view that the spectral regions where true absorption can take place are much narrower than was formerly believed (BOHR, Zeitschr. f. Phys. **13**, 162, 1923). 2. At all levels in the sun where Fraunhofer lines are supposed to originate, the pressure must be very low, much less than 1 atm. (ST. JOHN and BABCOCK, Astroph. Journ. **60**, 32, 1924). 3. For the limb-centre displacements no other explanation besides the one following from the dispersion theory seems to hold (JULIUS, Zeitschr. f. Phys. **27**, 23, 1924). 4. In an article on "Ionisation in stellar atmospheres" A. PANNEKOEK also concludes that in addition to selective absorption and molecular scattering there must be active in the sun another cause of extinction, at least ten times as effective as molecular scattering (B. A. N. **19**, 1922, p. 113). 5. From the defect of perspective foreshortening in spectro-heliograms (These Proceedings **27**, 451, 1924), and from stereoscopic observation of such documents we may infer that the photosphere must be transparent down to considerable depth.

[3]) From this point of view the Evershed effect has for the first time been dealt with in these Proceedings **12**, p. 278—279, 1910; more amply in Astroph. Journ. **40**, 1—32, 1914, and **43**, 43—66, 1916. The idea was then opposed by ST. JOHN, in Contrib. Mt. Wilson Nos 93 and 123 or Astroph. Journ. **41**, 28, 1915 and **44**, 1916, and again defended by the author in several articles on the dispersion theory of Fraunhofer lines (Verslag Akad. v. Wet. Amsterdam, **25**, 1245, 1917; These Proceedings **23**, p. 1113, 1921; **26**, p. 329, 1923; Astroph. Journ. **54**, 92, 1921).

Bull. **51,** 1916, has yet revealed certain peculiarities of the phenomenon which one has to keep in mind in any attempt to explanation. EVERSHED, in fact, adheres to the interpretation of the displacements as Doppler effects, but not without calling attention to some difficulties to which this leads.

The new data we have to consider bear upon a large spot which crossed the disc in 21° northern latitude between March 29th and April 12th 1915. The seeing was excellent. EVERSHED emphasizes that the displacements are larger with good definition of the penumbral image than would have been the case with an image more or less diffused along the slit by poor definition or long exposure time. So the characteristics of the phenomenon could be more sharply noticed than on former occasions. The computed horizontal radial velocities were found about 2.7 times larger than those observed by ST. JOHN for the corresponding line intensities — a discrepancy which is probably mainly accounted for by difference in magnitude of the observed spots or by unequal diffusion of the spot image on the slit-plate.

It was an important feature of these observations that the displacements have been measured *separately* at the opposite outer limits of the penumbra, each with respect to the average position of the line outside the spot (whereas ST. JOHN only gave the sums of the opposite displacements). Selected for measurement were a great many *Fe*-lines of intensities ranging from 0 to 6 of ROWLAND's scale, and besides a few lines of *Ni, Cr,* and *Ti*. The spot passed the meridian on April 4—5; several spectra were obtained before and after that passage and measurements made on 11 plates in total.

The known relation between the magnitude of the displacements and the line intensity showed quite clearly again; the shifts were greatest for intensities 0 and 1; they decreased as the intensities rose to 5 and 6. Moreover, a remarkable fact presented itself, which had not been noticed before: viz. that *the displacements were systematically greater in the penumbra directed towards the limb.* As on that side the shift is always towards the red, we may also state: *the displacements towards the red were systematically greater than those towards the violet.*

EVERSHED gives no explanation of this remarkable fact; he suggests that it may be an accidental circumstance, although the same phenomenon appears on some of his previous measures. The following table shows clearly, though, that the inequality is considerable and holds for all line intensities. Mean results are here given of a great number of observations relating to different positions of the spot on the disc and to various spectral regions. The figures represent kilometers per second, reduced to horizontal movement at the outer edges of the penumbra; the positive sign corresponds to receding motion.

On the basis of the Doppler interpretation we are thus led to the enigmatic conclusion that in the spot there would always be an excess of motion directed towards the limb of the solar disc. It appears impossible to conceive a circulatory process answering that peculiar condition, whatever vertical velocity components one might imagine for complementing the radial motion. This impossibility condemns the radial motion hypothesis.

	April 3, Spot East		April 6 and 7, Spot West.	
Line intensity	East penumbra	West penumbra	East penumbra	West penumbra
0 en 1	+ 2,73	— 2,02	— 1,41	+ 3,23
2	+ 2,19	— 2,04	— 1,21	+ 2,84
3	+ 2,14	— 1,59	— 1,08	+ 2,49
4	+ 2,02	— 1,66	— 1,06	+ 2,39
5 en 6	+ 1,09	— 1,41	— 0,90	+ 1,98

We are going to show that the dispersion theory of Fraunhofer lines suggests an adequate explanation of the observed peculiarity.

First, however, we should mention a few remarks made by EVERSHED with regard to line displacements observed when the slit was perpendicular to the radius of the solar disc.

On April 1 (spot near east limb) a shift was observed towards the red in the southern penumbra only; interpreted as a horizontal movement it would indicate a velocity of 0.64 km/sec. Two hours later: nearly equal displacements in north and south penumbrae, both about 0.46 km/sec.

On April 2 the same spot showed displacement towards the red at its northern edge only, corresponding to 0.9 km/sec. horizontal velocity; in the southern penumbra there was a slight shift towards the violet, 0.1 km/sec.

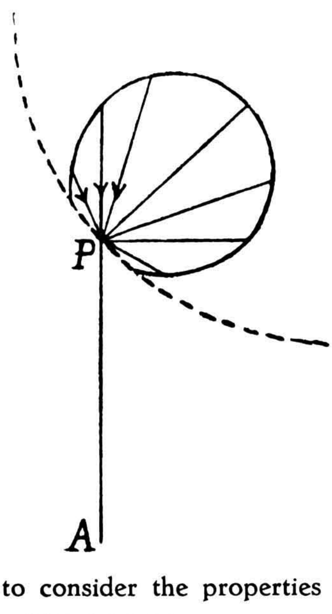
These displacements cannot represent a rotational movement of the spot, as the northern and southern shifts are not opposite. After the spot had passed the meridian, on April 9, a similar exposure with tangential slit gave, however, fairly opposite displacements north and south; reduced to horizontal movement:

northern penumbra: 0.65 km/sec.,
southern penumbra: — 0.88 km/sec.

Let us now suppose that this does represent a rotation, with a mean velocity of 0.77 km/sec. at the outer edge of the penumbra. The diameter of the spot was 41000 km.; a complete rotation would have taken 46 hours; so one might have expected a visible rotation of the (irregular) spot in a reasonable time. There was, however, no evidence of such change, when comparing the shape of the spot on successive days. Moreover, the direction of the rotation would not correspond to that found by HALE from the magnetic polarity of the spot. EVERSHED, therefore, considers it to be doubtful whether these line displacements really indicate rotation of the gases over the spot; he can only ascribe them to fortuitous, irregular movements.

It deserves notice that neither about the origin, nor about the consequences of violent solar storms (rotational or radial) any other evidence besides line displacement has ever been given by the observations. The circulatory system imagined by EVERSHED and ST. JOHN cannot, therefore, be said to constitute a necessary link in some series of conceptions; it depends entirely on the arbitrary hypothesis that the shifts are a Doppler effect. So we may safely abolish that supposition if we can dispense with it, as no connexion with other phenomena is thus broken.

Let us now consider the matter from the point of view of the dispersion theory. We start from the conception that in a sun-spot the optical density varies altogether irregularly, but increases on the average from the umbra outwards. Such a distribution of matter, existing in front of a luminous sphere, must show a peculiar distribution of light much like the known aspect of the umbra and penumbra of a sunspot. This could easily be explained geometrically using simple diagrams, and demonstrated by means of experiments with liquid drops of different refractive power[1]) and with whirling masses of gas[2]). From this conception of the nature of a sun-spot follows immediately, without any additional hypothesis, an explanation of the shifts of the Fraunhofer lines in the spot spectrum; we only have to take into account the unequal refractivity of the *R*-light and the *V*-light in the surroundings of each absorption line, and the characteristics of the Evershed effect will at once become manifest[3]).



The following representation of the rather intricate refracting process appeals perhaps somewhat more to the mind than the one given on former occasions, though it essentially rests on exactly the same principle.

Let *P* be a point somewhere in the solar atmosphere. It receives light from the various directions in quantities proportional to the radii vectores of the „surface of irradiation"[4]) (the mean shape of which is known from direct measurement of the distribution of brightness over the solar disc). We have to consider the properties of the light which, after having suffered ir-

[1]) These Proceedings **12**, 206, 1909.
[2]) Physik. Zeitschr. **15**, 48, 1914.
[3]) Astroph. Journ. **40**, (especially p. 19—25) 1914, and **43**, 43—66, 1916.
[4]) Handwörterbuch d. Naturwissenschaften VII. 830, 1912.

regular refraction in the region about P, emerges in the direction PA towards the earth. As regards the position of P in the spot region we distinguish the following two cases:

a. P is situated in the penumbra nearest to the sun's limb. According to our supposition the density is everywhere irregular, so that there are gradients in all directions. A gradient will be designated $+$ or $-$ if the density is either increasing or diminishing towards the edge of the disc. Consider the action of an arbitrary $+$ gradient on a certain R-light and a certain V-light, selected so as to have equal values of $n-1$. Then the R-light must have come from the left, the V-light from the right side; and, owing to the peculiar shape of the surface of irradiation, we immediately see that the weakening suffered by the R-light must be somewhat greater than the strengthening of the V-light.

Next consider the action of an arbitrary $-$ gradient on the same selected kinds of light. Now, with equal angular deviations, the weakening of the V-light will be more considerable than the strengthening of the R-light.

In both cases, therefore, if R-light and V-light are taken together, the joint result is a weakening. But because P is in the peripheral half of the penumbra, where the $+$ gradients are on the average higher than the $-$ gradients, the weakening of the R-light will be greater than the weakening of the V-light. This manifests itself as a displacement of the line towards the red.

b. P be situated in the penumbra farthest from the sun's edge. We again distinguish the case of a $+$ gradient and a $-$ gradient, and find once more that the weakening always predominates. At present, however, we are dealing with a region where the $-$ gradients have the advantage over the $+$ gradients, and where, therefore, the V-light will be more weakened than the R-light; the line appears to be shifted towards the violet.

The principal feature of the Evershed effect is thus accounted for. But what about the peculiarity afterwards stated, that on the peripheral edge of the spot the displacements are always greater than on the central edge?

This result too is easily understood on the basis of the dispersion theory. We are concerned with a consequence of the same circumstance upon which also depend the general displacement of Fraunhofer lines towards the red, and the limb—centre displacements in particular.

Indeed, the intensity of refraction effects is determined, for each wave-length, by the corresponding value of $n-1$. This quantity varies strongly in passing every absorption line; but as on an average the refractive index of the solar gases is greater than 1, the absolute value of $n-1$ will, as a rule, be greater on the red than on the violet sides of the absorption lines. And stronger irregular refraction generally involves increased weakening; so the average value of the shifts towards the red must exceed that of the shifts towards the violet.

It is interesting to notice that this single principle — which causes Fraunhofer lines to be asymmetrical to a degree fluctuating through the spectrum — correlates several classes of systematic line displacements, namely the general sun-arc displacements, the limb-centre shifts, and the preponderance of displacements towards the red in the Evershed effect. A very marked excess of displacements towards the red has also been found in prominences both at the limb and in disturbed regions on the disc [1]); it is not improbable that this is due to the same cause.

[1]) Transactions of the International Union for co-operation in Solar Research, Vol. IV, p. 128, 1914.