Radial Movement in Sun-spots. (*Second Paper.*)

By J. Evershed.

In the *Monthly Notices* for March 1909 I gave a preliminary account of some observations of line-displacements in the spectra of sun-spots,* and showed that the systematic nature of these displacements and their dependence on the position-angle of the spectrograph slit could be simply explained on the hypothesis of an outward radial movement parallel to the Sun's surface of the gases in the reversing layer over spots. It was necessary also to suppose that the movement accelerated outwards from the umbræ of spots, attaining a maximum value of about 2 km. per second at the outer edges of the penumbra. I have now to record the results of further investigations of the movements in spots which have been carried out during the past year.

At the outset it may be stated that the spectrum of every considerable spot appearing during the year, or reappearing after one or more rotations of the Sun, has been photographed at some time during its transit across the disc, and, without exception, all have shown the same systematic line-displacements. The lines have invariably been found to incline towards the red on the side of the spot nearest the Sun's limb, and towards the violet on the side nearest the centre of the disc, whatever position the spot may have occupied on the disc, if not too near the centre. In a few instances the motion has been detected even when the spot was on or very near to the central meridian.

If the displacements of the lines are really due to motion in the line of sight, as there seems no reason to doubt, the conclusion is, I think, inevitable that the above-mentioned hypothesis represents the truth, and that all spots are centres of a force directed radially outwards in a horizontal plane, acting continuously on the materials of the reversing layer over the entire area of a spot, and maintained throughout the life of a spot.†

* See also *Kodaikánal Observatory Bulletin*, No. 15.

† In a paper read before the Royal Academy of Sciences, Amsterdam, Professor Julius attempts to explain the systematic line-shifts in spot spectra by anomalous dispersion. In several important particulars, however, the facts I have observed do not conform with the consequences of this theory.

Professor Julius states that when the slit bisects the spot in the direction of the centre of the disc the Fraunhofer lines must be more or less curved in the shape of the letter S. This I have never observed, except in the case of the central absorption-lines of H and K. All the finer lines of the spectrum are quite straight, although inclined, over spots. Also the great majority of the lines are as sharply defined at their edges over the penumbræ where the displacement is greatest as on the general surface of the Sun, being displaced bodily from their normal positions. Anomalous dispersion would, however, cause a marked widening and indefiniteness at the edges, a spreading towards the violet on the side nearest the centre of the disc, and towards the red on the limb side.

Professor Julius' fundamental assumption that the gases above the photospheric level have densities sufficient to give appreciable refraction effects seems to me to be, on several grounds, highly improbable.

An interesting question which arises in connection with this radial movement is—Where is the source of supply? Where do the gases come from which are for months at a time continuously radiated away from the umbræ? Considering the most probable source to be the interior regions immediately beneath the reversing layer, or perhaps below the photosphere, I have attempted to discover vertical motion in the umbræ of spots, a welling up of gases from below. An upward movement at all comparable with the radial motion would be easily detected by line-displacements which, unlike those due to horizontal movements, would attain a maximum value for spots at the centre of the disc, diminishing with linear distance from the centre.

It is at once evident from a mere inspection of spectrum photographs of spots near the centre of the disc that this vertical motion is in all cases very small in comparison with the horizontal motion. A good series of spectra obtained specially with a view to determining vertical motion has not yet been secured, but some measures have been made of the lines in five different spot umbræ more or less well situated as regards the centre of the disc. No motion of ascent could, however, be detected in any of these; on the contrary, after correcting the measures for small displacements which I believe to be due to pressure effects, a small residual displacement was obtained towards the red, indicating a movement of descent in the umbræ of the order of 0·4 km. per second (details of these measures are given in *Memoirs of the Kodaikánal Observatory*, vol. 1, part i. If this result should be confirmed by future measures, and a motion of descent found to be general in spots, the inference would be that the source of supply was in the higher chromosphere, perhaps entirely outside the Sun. This would favour the views expressed by Mr. Newall in his recent Presidential address.*

On the other hand, it is perhaps unnecessary to assume any appreciable ascending motion, considering the probable enormous increase of density with the depth of the gases at the level of the photosphere. A practically unlimited quantity of the rarefied vapours of the reversing layer might be supplied from the denser regions a very short distance below, without any apparent movement upwards.

Radial Motion in the Higher Chromosphere.—I have said that the spectrum-lines are invariably found to be displaced towards the red on the side of the penumbræ nearest the limb, and to the violet on the opposite side, thus indicating an outward movement. There are, however, two notable exceptions among the host of absorption-lines in the solar spectrum. The central absorption-lines known as H_3 and K_3 (possibly also the underlying emission-lines H_2 and K_2), when clearly defined in the penumbræ, are displaced in exactly the opposite sense in every case I have examined, that is, towards the violet on the limb side of the spot, thus indicating an indraught of the calcium vapour of the higher chromosphere.

* *Monthly Notices*, lxix. 333.

In the following table I give a few measures of relative motion on opposite sides of the spots, showing that this inward movement is of the same order of magnitude as the outward movement of the lower gases.* The lines H_3 and K_3 represent, as is well known, a region extending roughly between 3″ and 10″ above the photosphere, whilst the bulk of the Fraunhofer lines showing the outward movement are produced in a region not exceeding 3″ in height.

TABLE I.

H and K in Spots, with Slit in Direction of Centre of Disc.

Date.	Central Distance. Radius = 1.	Approximate Latitude.	Relative Displacements in Å on opposite sides of Spot.		Deduced Horizontal Velocities. Mean of H and K.
1909.			H.	K.	Km. per sec.
Apr. 1	·68 E.	+ 9	0·037	0·039	2·1
7	·77 W.	− 10	0·029	0·040	1·7
Sept. 10	·60 W.	− 2	0·043	0·016	1·8
14	·98 W.	− 3	0·059	0·051	2·1
Nov. 11	·91 W.	− 7	0·047	0·024	1·5
14	·65 E.	− 4	0·043	0·046	2·6
,,	·71 E.	− 7	0·025	0·016	1·1
30	·73 W.	− 14	0·040	0·032	1·8
,,	·52 W.	− 13	0·023	0·028	1·8

Average horizontal velocity = 1·83 km. per sec. on each side of a spot near outer limits of penumbra.

The direction of motion is in all cases one of approach on the side nearest the limb, and of recession on the side nearest the centre of the disc, and the greatest motion is found near the outer edge of the penumbræ.

Now it is interesting to note that whilst the lines of the reversing layer appear perfectly straight, but inclined, where they cross a spot, there being an appreciable break or jolt in the lines at the points where they pass from the penumbræ on to the surrounding photosphere, this is not the case with H and K, which generally form regular sinuous curves over spots when the slit lies in the direction of the Sun's centre. With the slit in the opposite direction they, in common with the other absorption-lines, remain perfectly straight and undisplaced provided that no eruptive disturbance is in progress. The following diagram (fig. 1) will give a general idea (much exaggerated) of the behaviour of H and K as contrasted with a line of iron when the slit is in the direction of the centre, or radial at the limb.

* In the table it will be noticed that H and K in some cases give discordant values of the displacement. This is due to the difficulties of measurement: frequently the narrow absorption-lines H_3 and K_3 are absent on one side of the spot, and the settings have then to be made on the much more diffuse emission-lines H_2 and K_2.

An explanation of this contrasted behaviour of the Ca and Fe lines is suggested by Professor Michie Smith: it is that the low-lying metallic vapours in their motion outwards penetrate into or even perhaps beneath the banked-up faculæ surrounding the spot, so that there is an apparently sudden stoppage of the motion at the limits of the penumbra. The calcium vapour of the higher region, on the other hand, in its movement inwards towards the umbra, meets with no such obstruction; the motion can therefore be traced from a considerable distance outside the penumbra.

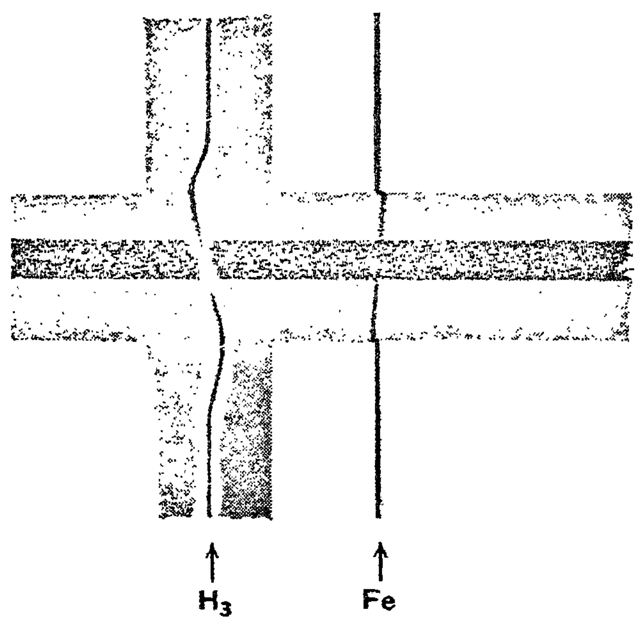

FIG. 1.

The inclination of the calcium lines crossing the spot would seem to indicate a diminishing velocity towards the umbra, just as the opposite inclination of the other lines indicates an accelerated movement. This, however, cannot be affirmed until it has been shown that there is no vertical motion in the calcium vapour. It would seem natural to suppose that the calcium vapour is drawn downwards as well as inwards, and I cannot at present say whether this is so or not, although some of my measures indicate such a downdraught.

Spiral Motion of the Outflowing Gases.—In the preliminary account of these researches already referred to it was stated that the greatest line-displacements were found when the spectrograph slit bisected a spot in the direction of the centre of the disc; and that if the Sun's image were turned through 90°, so that the slit was parallel to the tangent at the nearer limb, the displacements disappeared. This nodal position of the slit implies an outward movement in straight lines from the umbræ, whereas any slight displacement of the nodes from 90° would mean that, superposed upon the radial movement, there was a relatively slow rotation.

Combining the two movements, there would result a spiral motion, the gases flowing outwards in more or less curved lines.

The examination of good spectroheliograph images, and visual observation of the radial filaments in the penumbræ of spots, suggested that in many cases at any rate the motion *is* in curved lines, if these filaments represent, as I think they must do, the actual stream-lines of the moving matter. To test the matter, I have selected from our collection of photographs a few spectra for measurement in which the following conditions have been fulfilled:—

1. Spectrograph slit exactly normal to direction of centre of disc.

2. Spot not less than half way from the centre towards the limb.

3. Atmospheric conditions good.

4. Scale of spectra not less than 1 mm. = Å.

If there should be a displacement of the line of nodes of several degrees in either direction from the normal (tangent at the limb), minute but measurable displacements of the lines on each side of a spot should be found.

The method adopted in measuring the plates was in most cases similar to that used for determining pressure shifts in spot spectra (described in Memoir No. 1 of the Kodaikánal Observatory), using a sliding screen placed over the negative to limit the field of view alternately to separate parts of the image, and using a single thread placed parallel to the spectrum lines In two spectra it was found advantageous to measure the double displacements resulting from the superposition of a pair of positive copies of each negative by a laborious method, which, however, gives smaller probable errors than the direct method.

In all the spectra measured, unmistakable evidence of small displacements of the lines at the north and south edges of the penumbræ was found, indicating a displacement of the line of nodes amounting in the mean to about 8°.

I give in Table II. the results of these measures, expressed in km. per sec. I have assumed that the observed motion is the component in the line of sight of a motion parallel to the Sun's surface. My justification for this rests, it must be admitted, on very meagre negative evidence, having so far found no appreciable vertical motion in the penumbræ when situated near the centre of the disc. The observed velocities may be found by multiplying the tabulated velocities by the figure given in column 2, which is the sine of the angular distance of the spot from the centre of the disc. The observed velocities are always a little smaller, according to the distance of the spot from the limb, where the component in the line of sight of a horizontal movement becomes unity.

[TABLE.

TABLE II.

Slit normal to Direction of Sun's Centre.

Date.	Central Distance. Radius = 1.	Latitude. Degrees.	Horizontal Motion. Km. per sec. N.	S.
1909 March 6	·81 W.	− 9	−0·32	+0·32
,, ,, ,,	·57 W.	+ 3	+0·37	−0·37
,, April 7	·77 W.	−10	−0·17	+0·49
,, July 28	·80 W.	+ 7	+0·32	−0·32
,, Sept. 11	·78 W.	− 2	−0·64	+0·24
		Means	0·36	0·35

Note.—The values obtained in the first and second determinations (March 6th) are the mean movements of the north and south edges of the penumbrae. The method of measuring does not in these cases admit of separate estimates at the two sides of the spots except as regards sign. The same remarks apply also to the measurement of radial motion on July 28th given in Table III.

The velocities found are all of the same order of magnitude, and indicate an average movement of about ⅓ of a kilometre per second on each side of a spot. The measures were made at the outer limits of the penumbra in each case, where the displacement of the lines is greatest.

This movement, found at the extremities of a diameter normal to the direction of the Sun's centre, and roughly north and south, probably indicates a rotation of the gases at the outer edges of the penumbrae. But it may mean simply an easterly or westerly drift on the north and south sides of a spot. The question can only be decided by means of similar measures made on spots situated near the central meridian, when a normal to the direction of the centre will bisect the spot in an east and west direction. If the motion at the extremities of an east and west diameter were found to be the same as at the north and south, a circulating movement could be affirmed. Unfortunately, the displacement of the lines is too minute to be detected except with a spot situated more than half way from the centre towards the limb.

The movement measured cannot be due to the relative motion which would be acquired by particles moving radially from the spot in a north and south direction (analogous to the deflection of the trade winds on the Earth), for this could not exceed 0·015 km. per sec. after travelling over 1° of solar latitude, or a distance about equal to the radius of a moderate-sized spot. Moreover, the motion would be opposite in direction to that actually found; that is to say, for a north spot there would be a westerly drift on the north side, and an easterly drift on the south side.

This would become, for a spot approaching the west limb, a recession on the north side and an approach on the south side of the spot, relative, of course, to the surrounding undisturbed surface of the Sun. On referring to Table II., it is at once seen that the two northern spots give a + movement and the three southern spots a − movement on their northern sides.

If we assume a rotational movement, the change of signs revealed in the measures, in passing from a northern to a southern spot, is interesting as indicating an opposite direction of rotation in the two hemispheres, the direction being clockwise in the south.

For comparison with the above, I give in Table III. the horizontal radial velocities of the same spots, deduced from measures of spectra taken with the slit in the direction of the centre of the disc. Here we have no change of sign with change of hemisphere, but always a motion of approach on the east and recession on the west sides of spots nearing the west limb, that is, of approach on the side nearest the centre of the disc. This is, of course, the effect of the radial movement; and proof that it is in all directions from the spot has been obtained by observing the displacements in spots on the central meridian, and in other situations on the disc.

TABLE III.

Slit in Direction of Sun's Centre.

Date.	Central Distance. Radius = 1.	Latitude. Degrees.	Horizontal Motion. Km. per sec. E.	W.
1909 March 4	·43 W.	− 9	+ 3·09	− 3·50
,, ,, 6	·57 W.	+ 3	+ 2·60	− 1·93
,, April 7	·77 W.	− 10	+ 1·26	− 2·34
,, July 28	·80 W.	+ 7	+ 1·30	− 1·30
,, Sept. 10	·60 W.	− 2	+ 1·10	− 2·08
		Means	+ 1·87	− 2·23

Summarising these results, we have a mean rotational movement of 0·35 km. per sec., and a radial motion of about 2 km. per sec. Combining them, we get a spiral or catharine-wheel movement opposite in the two hemispheres. This is represented graphically in the appended diagram (fig. 2), which shows the directions of the stream-lines in a northern and in a southern spot.

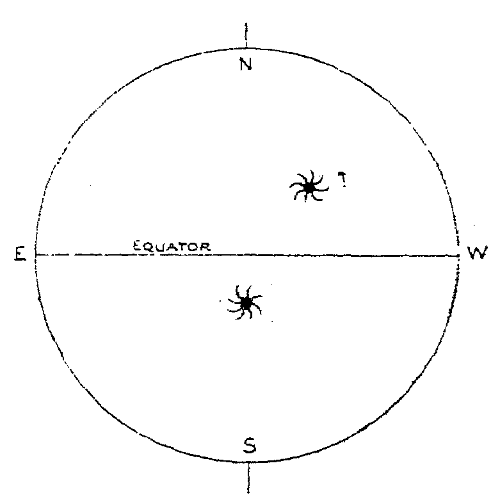

FIG. 2.

It might be supposed that a spiral movement such as that here illustrated would betray itself in the disposition of the calcium flocculi over spots. It is to be remarked, however, that the circular movements I have described are confined entirely within the penumbral limits, and no motion has yet been detected outside those limits. Also it appears to be confined to the lower chromosphere. In good spectroheliograph plates of the calcium flocculi the regions of the penumbræ in quiet spots often show radial stream-lines, and these are sometimes curved. In general, however, the more brilliant masses of flocculi of the surrounding region show no tendency to either a radial or a spiral structure, although the outlying portions frequently break up into circular or horseshoe formations, which are seen in an attenuated form all over the disc. But the minute structure of these rings is always granular, and gives no suggestion of a whirling motion.

It was at first rather baffling to find that these spirals are reversed in direction compared with the stream-lines shown in some of Hale's H_α photographs. This reversal is, however, readily explained if we assume that the hydrogen represented in Hale's plates partakes of the indraught which I have shown occurs in the higher chromosphere from the behaviour of the lines H and K. If the inflowing gases of the higher regions and the out-flowing gases of the reversing layer all partake of a slow rotational movement, then we should have oppositely curved spirals in the two regions.

I shall not discuss at length the bearing of these results on the Zeeman phenomena of spots, mainly because my measures as regards rotation are preliminary only, and will probably be modified by future research; I cannot say whether the movement is universal in spots. The apparently radial structure, without curvature, in the penumbral filaments, often seen in symmetrical spots, suggests a purely radial movement in many cases.

The opposite movement in the two hemispheres, although clearly shown in five instances, may not be an invariable rule. Referring to the magnetic field in spots, Professor Hale states that "Although the larger spots in the northern and southern hemispheres of the Sun are usually found to be of opposite polarity, it frequently happens that spots of opposite polarity occur in the same hemisphere, sometimes in the same spot group." * One would expect, therefore, if the rotation movement bears a causal relation to the magnetic field, to find occasional instances of spots showing a clockwise rotation in the north, or *vice versa*.

It appears to be extremely doubtful whether this apparent rotational movement will, by assuming an ionised condition of the moving gases, be found adequate to explain the magnetic field. So far as my observations go, the motion seems always to be greatest at the outer edges of the penumbræ, and it becomes quite imperceptible in the umbral region; yet the Zeeman broadening of the lines is, I think, invariably greatest over the umbræ, and decreases to an inappreciable amount at the outer edges of the penumbræ.

* *Publications of the Astronomical Society of the Pacific*, xxi. 20[illegible]

It is perhaps more probable that the characteristic movements (radial and rotational) taking place in the penumbræ are secondary effects, and that the electric vortex is entirely beneath the reversing layer. Professor Hale has found that the magnetic field decreases rapidly with height above the photospheric level :—

"The doublets and triplets of iron give the strongest fields hitherto measured in sun-spots. The D lines of sodium and the *b* lines of magnesium, which are produced at a higher level in the solar atmosphere, indicate a much weaker field. The hydrogen line over sun-spots, representing a still higher level, give no indication of a magnetic field." *

There is a remarkable and perhaps significant analogy in this with the radial-motion effect. I have found that the greatest motion of 2 to 3 km. per sec. is found in the region of iron absorption. The line D_1 of sodium is scarcely, if at all, affected on the few plates I have taken of this region of the spectrum (D_2 is apparently unaffected, but an interfering atmospheric line at 5890·10 will perhaps account for this).† The *b* lines of magnesium are affected more than D_1, but much less than the neighbouring iron lines. Hydrogen, if affected at all, seems to show traces of an opposite movement, as is shown by the lines H and K of the higher chromosphere.

It may be well to state here that in measuring the displacements due to radial motion I have usually selected lines having an intensity not greater than 4 on Rowland's scale. These are mostly iron lines, but include also the lines of Co, Ni, Cr, V, and Ti. Most of the stronger lines appear to give much smaller values of the motion, and there is a tendency among the fainter lines to give a rather wide range of values, even among lines of the same element. Probably the movement varies enormously with level, and the values I have given in Tables II. and III. must be taken to represent the region of greatest motion.

A thorough investigation of the differences found among the different lines of an element, as well as between those of the different elements, is very desirable; but progress in this direction has been slow, partly owing to the numerous other lines of inquiry opened up, and also to the laborious nature of the measuring work.

* *Loc. cit.*, page 207.

† The sodium lines at 5682·869 and 5688·436 give much larger values of the radial motion than D_1, but not so large as the average of the iron lines measured.