Kodaikánal Observatory.

BULLETIN No. XV.

RADIAL MOVEMENT IN SUNSPOTS.

Displacements of the lines of hydrogen and calcium in the neighbourhood of sunspots, indicating violent motions in the line of sight, is a common characteristic of spot disturbances. Such phenomena are frequently observed during periods of active change in spot development, or during the genesis of a spot. These line-shifts rarely affect the spectra of other elements than those of the higher chromosphere. In very violent outbursts, in addition to the hydrogen and calcium lines, those of He, Mg, Na, and some of the enhanced lines of Fe are occasionally seen to be affected, but to a much less extent than those of H and Ca. The displacements may be either an increase or a decrease of wave-length, and may amount to several Ångström units, indicating movements of approach or recession of several hundred kilometers per second. These movements are seldom maintained for more than a few minutes at a time, and are usually to be found in the immediate neighbourhood of spots, rarely within the umbral area.

Recently line-shifts of quite another character have been photographed here. These are apparently permanent, affect a very large proportion of the Fraunhofer absorption lines, and are only found in the penumbræ of spots.

In the course of measurement of a large number of spot spectrum plates obtained here, it was noticed that the position of the lines of the true umbral spectrum seem usually to be almost entirely unaffected by motion in the line of sight. It is true that very slight displacements towards the violet appear to be indicated in a series of measures of some of the best plates, but the amount of the displacement (about 0·004 Å) is scarcely larger than the limits of error of measurement. In these plates the scale is about 1Å = 0 67 mm., and any movements of the solar gases of less than ½ km. per second would be too small for detection.

In some spectra obtained this year, in the fourth and fifth orders of a 3·2 inch grating,* in which the scale is 1Å = 1·0 to 2 mm., the displacement of the lines in the umbræ of spots is still barely measurable, but very obvious displacements are found in the penumbræ; and this shift turns out to be of a most interesting character, and is apparently a constant feature of all spots. That it should have escaped detection hitherto is most surprising, considering the high dispersion now employed in all spot spectrum work.

The first plate showing this feature clearly was exposed on January 7, 1909, using the fourth order of the grating. It covers the region λ 4650 to λ 4790, and the scale is 1Å = 1·08 mm. An unusual amount of detail is visible in the umbral spectrum, which is no doubt due to the clearness and steadiness of the air at the

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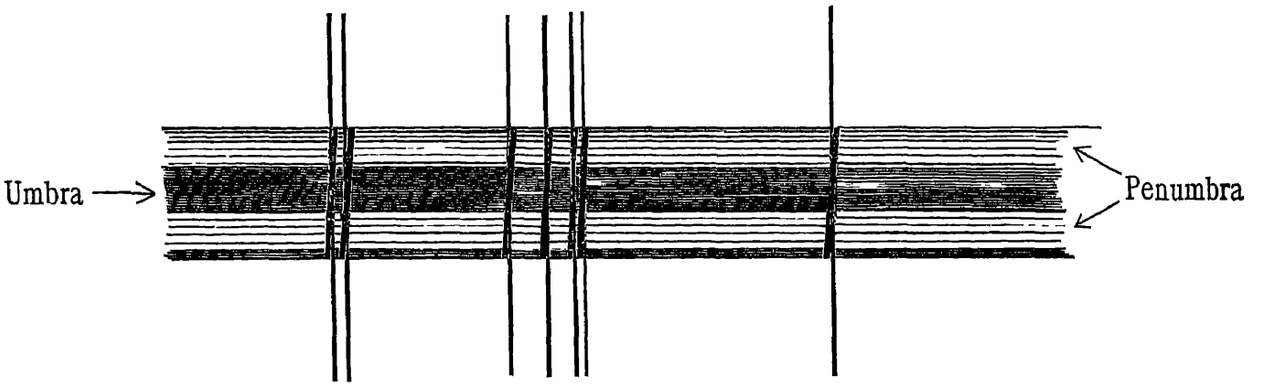
* A Rowland grating of 3·2 inches ruled surface and 14,458 lines to the inch.

time of exposure. The general appearance of the Fraunhofer lines crossing the spot is represented in the accompanying diagram



in which the displacements are somewhat exaggerated, to show their character The lines appear to be about equally displaced, but in opposite directions, on the two sides of the spot. There are, however, considerable differences among the different lines, the stronger lines appearing less affected than the fine narrow ones.

A preliminary measurement of ten of the best defined lines gives a mean total displacement, measured at the outer edges of the penumbra, of 0·027 Å, indicating a receding velocity on the north-west side of the spot of 0·86 km. per second, and an approaching velocity of the same amount on the south-east side, the position angle of the north end of the spectrograph slit being 314°. The spot photographed was in latitude 9° N, and was 31° W of the central meridian

The appearance of the lines in this photograph at once suggested a rotation of the absorbing gases in the spot, not a vortex movement but a rotation of the spot as a whole about a point at its centre. The lines seem quite straight over the spot, but inclined one or two degrees to the undisturbed lines.

The hypothesis of circular motion of any kind has proved, however, to be certainly untenable. From an examination of about 150 spectra obtained since January 7 and representing seven spots in the northern hemisphere and four in the southern, the following statements may be made :—

(1) All the spots examined show line-shifts of about the same order of magnitude, when at the same distance from the centre of the disc

(2) The displacements disappear when the spot is within 10° of the centre

(3) The displacements are most evident when the spot is between 30° and 50° from the centre of the disc, but are difficult to photograph when quite near the limb.

(4) The displacements are of opposite sign on opposite sides of the central meridian when the slit is parallel to the solar equator.

(5) The displacements are invariably towards the violet on the preceding side of a spot, towards the red on the following side, when the spot is east of the central meridian ; the reverse when west.

(6) Southern spots show the same direction of movement as northern.

(7) No displacements are observed when the slit bisects a spot in a direction at right angles to a line joining the spot and the centre of the sun's disc.

A hypothesis which seems in harmony with all the facts here stated, is one which attributes the displacements to a radial movement outwards from the spot-centre. The motion must be essentially horizontal, or parallel to the sun's surface. This is shown by the total disappearance of the line-shifts when the spot is near the centre of the disc. The hypothesis of a vortex, or rotation of any kind, about an axis perpendicular to the sun's surface, is negatived by the fact stated in paragraph 7, for it is evident that for a circular movement a nodal point should be found when the slit bisects the spot in a direction passing through the centre of the sun's disc, the maximum displacement occurring in a direction at right angles to this. This direction of the node, however, differs from that actually found by about 90°.

To obtain evidence on this crucial point, advantage is taken of the rotation of the solar image due to the action of the heliostat. Thus, in the interval between 8 A.M. and 5 P.M. the position angle of the slit, which is fixed truly vertical, changes through about 100°; the north end of the slit passing from P.A. 300° to 40° and being at 360° at solar noon. Different sections through a spot can therefore be obtained by simply taking a succession of photographs at intervals throughout the day. Now it has invariably been found that the displacements diminish in amount from 8^h up to about 11^h when they generally disappear entirely, reappearing with opposite signs in the afternoon; but the time of no displacement does not occur exactly at solar noon, and the evidence so far obtained indicates that the line of nodes coincides with the direction at right angles to the line joining the spot and the centre of the disc, as it should do if the motion is radial.

The whole of the evidence obtained up to the time of writing, is presented in the accompanying table. In this all the photographs obtained are entered in the order in which they were taken, with the exception of a few duplicate exposures made on the same spot at the same time, which are omitted to save space. The third column gives the calculated position angle of the north end of the spectrograph slit; the fourth column gives the reference number of the spot; the succeeding columns give the approximate latitudes, and the longitudes reckoned east or west of the central meridian. These co-ordinates were read off from the daily spot-charts prepared at this observatory. The column headed "Shift at north side of spot" indicates by the letters V and R the direction of the displacement, whether to violet or red, and the small letters following give a rough idea of the amount of displacement, viz, l = large, m = medium, s = small, and tr = a just appreciable trace.

The following points are evident from the table:—

When the position angle of the north end of the slit is between 297° and 330°, eastern spots always give a violet shift on the north side, western spots a red shift.

Between 330° and 360°, the shift is either absent, or very minute in either direction.

From P A 20° to 70°, the shifts are, with one doubtful care, to the red for an eastern spot, and to the violet for a western.

Finally, spots near the centre show no shift at all.

Since the position angle of the slit when no displacements are observed is of fundamental importance in determining the character of the movement, it may be well to refer in detail to the photographs bearing on this point Take first the eastern spot, No. 1595, on January 27: six photographs of a central section of the spot were obtained at intervals during the day. The exposure times, position angle of the slit, and observed direction of shift are here repeated as follows:—

Exposure time.	P.A. north end of slit.	Shift at north side of spot.
H. M.	°	
8 4	299	V l
8 57	312	V s
11 27	346	R tr
11 58	352	R s
15 45	43	R m
16 7	48	R l

The change from a violet to a red shift occurs between $8^h\ 57^m$ and $11^h\ 27^m$, when the north end of the slit was between position angles 312° and 346°. Assuming the mean angle, the change would have occurred at P.A. 329°, or 31° to the west of north. The position angle of the spot, measured from the centre of the disc, was 60°, *i.e.*, 60° to the east of north; therefore, the angle between the line of nodes and the direction of the centre of the disc would be 60° + 31° = 91°.

Again, take the western spot No. 1591 on January 26. This was photographed four times, and the change from a red to a violet shift occurred between $12^h\ 2^m$ and $14^h\ 27^m$, or between P.A. 353° and 25°: the mean angle between these is 9° to the east of north, and the position angle of the spot was 88° west of north,

so that the angle between the line of nodes and the centre of the disc is 97°. I summarize below all the instances where the shift was observed on both sides of the line of nodes :—

Date.	Spot number.	Position angle of spot.	Position angle of node.	Angle between node and centre of disc.
		°	°	°
January 18	1588	82 E	20 W	102
Do. 18	1591	74 E	2 W	76
Do 20	1591	60 E	23 W	83
Do. 24	1594	87 E	8 W	95
Do 25	1591	84 W	0	84
Do. 26	1591	88 W	9 E	97
Do. 27	1595	60 E	31 W	91
				Mean 90

The estimate of the time when there is no shift must necessarily be extremely uncertain considering the small amount of the displacements, even when at their maximum, and the accordance in the above table is really remarkable, and testifies to the sensitiveness of the eye to very minute deviations from straightness in the spectrum lines.

It may be well to mention here that tests of the reality of these minute line-shifts have been applied in two ways First, by photographing the spot spectrum in the red, in the region including the well-known group of solar and telluric lines used by Dunér and Halm in their determinations of the solar rotation. In this group, the telluric oxygen lines are very narrow and well-defined, whilst the solar iron lines are comparatively broad, and are indeed much widened in spots.* Since the displacements are much more conspicuous in the finer lines of the spectrum, the oxygen lines should show the effect strongly, if it is spurious. In the photographs, however, they are found to be absolutely straight, whilst the iron lines beside them are bent.

The second test was applied at a time when the slit was approximately in the position angle of the line of nodes for a spot which was east of the central meridian, and photographs of a central section of the spot showed no shift. Photographs were then obtained of the preceding and of the following edges of the penumbra Here the line-shift should be at a maximum, and, as expected, the lines were found to be evenly bulged, to the violet on the preceding edge and to the red on the following edge.

It is somewhat disappointing, perhaps, that the hypothesis of a radial movement in spots, which is so strongly supported by these observations, seems entirely out of harmony with the splendid discovery of the Zeeman effect in sunspots made by Professor Hale. This seems to demand a vortex, or at any rate a circular movement in sunspots; and it was only after a considerable amount of evidence had accumulated, that the preconceived conviction that the motion must be circular was abandoned. A consoling feature of this new theory of spot movement is that it seems to explain the radial structure of the filaments in the penumbræ of spots, and the radial disposition of the calcium flocculi immediately surrounding a well-developed symmetrical spot. It also harmonizes with the well-known tendency of the principal spots in a group to separate, the leader advancing, and the follower receding.

A difficulty should also be mentioned. When the slit centrally bisects a symmetrical spot, in a direction approximating to that giving the greatest shift, the displaced lines appear quite straight, as before mentioned, and inclined to the undisturbed lines, the greatest shift occurring at the outer limits of the penumbra. This seems to imply accelerating movement, from the centre of the spot outwards, yet at the limits of the penumbra the motion apparently ceases abruptly. It is hoped that further research will throw light on this and other obscure points.

* The Fe line at 6302·709 is seen to be beautifully doubled in the third order spectrum of all spots examined by me.

KODAIKÁNAL,
3rd February 1909.

J. EVERSHED.

LINE SHIFTS IN SPOT SPECTRA.

Date.	Hour.	P.A. North end of slit	Number of spot.	Latitude.		Longitude.		Shift at north side of spot	Remarks.
				+	−	E.	W		
1909.	H. M.	°	°	°	°	°	°		
January 5.	11 11	344	1578	7	...	...	27	R, s	Definition poor.
	33	348	—	7			27	R, s	
	16 0	348	—	7			30	V	
Do. 7.	8 47	310	1580	9	...	...	32	R, l	
	9 45	324	—	9			32	R, l	
	10 15	331	—	9			32	R, m	
	11 11	343	—	9			32	R, m	
	33	348	1578	7			53	R, m	
Do. 8.	9 5	315	1580	9	...	...	44	R, l	
	11 0	341	—	9			44	R, s	
	10 24	333	1578	8			66	R, s	
Do. 9.	8 44	310	1580	10	...	...	58	R, l	
	10 25	333	—	10			58	R, s	
Do. 11.	10 18	331	1588	10	...	20	...	—	No certain shift either way.
	45	337	—	10		20		—	
Do. 15.	9 30	321	1583	9	...	...	32	R, l	
	49	324	—	9			32	R, l	
	10 0	327	—	9			32	R, l	
	32	333	1588		2	63		V, l	
	37	335	1590		12	75		V, s	Very small spot.
Do. 16.	8 8	301	1588		3	50	...	V, l	
	51	311	1583	9			45	R, l	
	9 57	326	1590		13	61		V, s	Distinct, but a very small spot.
	10 1	327	1591	7		80		V, s	
	4	328	1588		3	50		V, l	
Do. 17.	8 10	301	1588	...	4	37	.	V, l	
	14	302	1583		7		58	R, l	
	20	308	1591		7	66		V, l	
	10 9	327	1590		13	48		V, s	
	15 28	40	1588		4	35		R, s	H and K region.
	32	40	1583	7			58	V, s	
	37	41	1590		14	46		—	Poor definition.
Do. 18.	7 57	298	1588	...	3	24	...	V, s	
	8 24	304	1591	7		53		V, m	
	29	306	1588	9			75	—	Spot poorly defined.
	9 3	313	1588		3	24		V, tr	
	10	315	1591	7		53		V, s	
	10 56	340	1588		3	24		—	Good definition, no shift.
	11 6	341	1588	9			75	R, l	
	15 30	40	1588		3	21		R, tr	
	34	41	1591	7		50		R, s	Poor definition.
	40	42	—	7		50		R, l	Fair definition.
	57	46	—	7		50		R, l	
	16 2	47	1588		3	21		R, tr	
	7	48	1591	7		50		R, m	
	16	51		7		53		R, m	
Do. 19.	9 12	316	1591	7		38	...	V, m	
	16	317	1588		3	10		—	No shift.
	52	325	1591	7		38		V, s	
	56	325	1588		3	10		V, tr	
	29	326	1591	7		38		V, s	
Do. 20.	8 16	303	1591	7	...	25	..	V, s	
	20	303	1588		3		3	—	No shift.
	29	306	1591	7		25		V	Poor focus.
	10 15	330	—	7		25		—	No shift.
	48	337	—	7		25		—	
	11 46	350	—	7		24		R, tr	
	15 11	36	—	7		23		R, tr	Spot poorly defined.
	16 23	52	—	7		23		R, tr	
Do. 21.	7 58	298	1591	7	..	14	..	V, tr	
	8 2	299	1588		4		16	R, tr	
	51	311	1591	7		14		—	No shift.
	42	309	1588		4		16	—	

Date.	Hour.	P.A North end of slit.	Number of spot.	Latitude.		Longitude.		Shift at north side of spot.	Remarks.
				+	−	E.	W.		
1909.	H. M.	°	°	°	°	°			
January 21—*cont.*	14 58	33	1591	7	...	12	...	R, tr	
	15 27	39	1588		3		17	V, s	
Do. 22.	8 4	300	1588		3		29	R, s	
	28	305	1591	10		1		—	No shift.
	42	309	1590*a*		13		20	—	Very small spots.
	48	310	1590*b*		17		17	—	
Do. 23.	7 57	298	1588		4	..	41	R, m	
	8 6	300	1591	6			12	R, s	
	22	304	1590		13		32	—	No shift.
	30	306	1588		4		41	R, m	
	43	309	1593	8		73		V, m	
Do. 24.	8 39	308	1588		4	...	55	R, m	
	42	309	1591	6			24	R, m	
	52	311	1593	8		61		V, m	
	10 47	337	1591	6			24	R, m	
	11 13	343	1592		16	46		V, m	
Do. 25.	7 53	297	1594*a*	..	8	53	..	V, l	
	57	298	1594*b*		9	58		V, l	
	8 2	300	1591	6			37	R, l	
	9 17	317	1594*b*		8	57		V, l	Following spot.
	19	317	1594*a*		8	53		V, l	Preceding spot.
	22	318	1593	9		47		V, l	
	28	319	1595	10		66		V, l	
	56	325	1595	10		66		V, m	
	59	326	1593	10		47		V, s	
	10 4	327	1592		15	35		V, m	
	8	328	1591	6			37	R, l	
	14 20	24	1591	6			39	V, s	
	28	25	1593	9		46		R, s	
	29	25	1594*b*		9	58		R, s	Following spot.
	17 28	67	1593	9		43		R, s	
	31	68	1595	10		66		R, m	
	37	69	1594*a*		8	53		R, m	Preceding spot.
	42	70	1591	6			40	V, l	
Do. 26.	7 55	297	1594*a*	...	9	38	..	V, m	Preceding spot.
	58	298	1594*b*		9	46		V, m	Following spot.
	8 4	300	1594*a*		9	38		V, m	Preceding spot.
	7	300	1595	9		52		V, m	Plate under-exposed.
	10 22	331	1594*a*		9	38		V, l	Preceding spot.
	23	333	1594*b*		9	46		V, l	Following spot.
	31	333	1593	9		34		V, s	
	54	334	1595	9		52		V, s	
	38	335	1591	6			52	R, l	Shift greater on south side.
	11 55	352	1594*a*		9	37		V, s	Preceding spot.
	58	352	1595	9		51		R, s	
	12 2	353	1591	6			54	R, s	
	14 19	23	1595	9		50		R, m	
	27	25	1591	6			54	V, s	
	16 20	51	—	6			55	V, m	
	28	52	1595	9		50		R, m	Spot poorly defined.
	17 26	67	—	9		49		R, l	
Do. 27	8 4	299	1595	9	..	39	.	V, l	
	57	312	—	9		39		V, s	
	59	313	—	9		39		V, s	Following edge of penumbra.
	9 2	313	—	9		39		V, tr	Preceding edge.
	4	313	—	9		39		R, tr	Following edge.
	11 25	345	—	9		38		R	Do.
	27	346	—	9		38		R, tr	Centre of spot.
	30	346	—	9		38		V	Preceding edge of penumbra.
	57	352	—	9		38		V	Do.
	58	352	—	9		38		R, s	Centre of spot.
	12 0	353	—	9		38		R	Following edge of penumbra.
	15 45	43	—	9		36		R, m	Centre of spot.
	16 4	47	1596	10		60		R, l	
	7	48	1595	9		35		R, l	
	12	49	1591	6			70	V, l	

In the fourth column *a* and *b* refer to the preceding and following members of a group.

ADDENDUM—*February* 23.

Since these observations were made a device has been added to the spectrograph by means of which the sun's image can be rotated on the slit through 90°. The results obtained in this way leave no doubt whatever as to the position of the line of nodes, for wherever a spot may happen to be situated on the disc, outside the limit of 10° from the centre, where the shift becomes inappreciable the motion is always found to be greatest when the slit bisects a spot in the direction of the centre of the disc, and to disappear altogether when the slit is at right angles to this direction.

The greatest shift observed with the slit in the direction of the centre of the disc was on a plate exposed on February 4, representing a spot in longitude 41° west, and latitude 7° north The spectrum includes 100 units between λλ 4782 and 4885, and all the lines in this region show the motion shift, with the probable exception of $H\beta$, which is as usual narrowed in the spot, but seems otherwise unaffected. All the lines are not equally affected, but a large proportion are inclined over the spot a little more than one degree compared with the normal direction of the undisturbed lines. This corresponds to a maximum displacement at the outer edges of the penumbra, on each side, of 0·017 Å, indicating a velocity of approach on the following side and recession on the preceding side of the spot of 1·05 km. per second. But this is the component of velocity in the direction of the earth. The actual velocity parallel to the sun's surface is found by dividing the observed velocity by the sine of the angular distance of the spot from the centre of the disc, which was 42°. Thus, 1·05/0·67=1·57 km. per second. This represents for the majority of the lines the maximum speed attained by the projected matter on reaching the outer limits of the penumbra. Some of the lines, however, indicate a speed of over 2 km., and others under 1 km per second, whilst it is possible, from the behaviour of $H\beta$ that the elements in the higher chromosphere do not share in the movement.

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