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NEW MEASURES OF RADIAL MOTION IN SUNSPOTS.

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During the years of minimum sunspot activity, very few opportunities have occurred at Kodaikanal for extending knowledge of the movements taking place in spots, beyond what could be gathered from the first series of sunspot spectra obtained in the year 1909, which led to the discovery of the radial movement. It was realized that in order to make any advance it was useless to attempt to photograph spot spectra under conditions of poor definition of the spot on the slit of the spectrograph. Also, when definition was at its best, means must be employed for reducing the exposure time to the minimum possible consistent with high dispersion, in order to get clear spectrum images of details of the spots themselves.

Early in 1915 it was found possible to reduce greatly the exposure times by employing the new Anderson grating, which has a much larger ruled area than either of the gratings previously used, and is also very bright in the third order. In addition, the Observatory had acquired on loan from the Nizamiah Observatory a lens of 15 inches diameter and 15 feet focus, which I mounted temporarily on a moving carriage running on rails passing in front of the siderostat, so that when other apparatus was not in use the lens could be run into position in front of the siderostat mirror, giving an image of the sun about 40 mm. diameter on the slit of the spectrograph. This lens was found to be more efficient in the blue and violet part of the spectrum than the parabolic silver-on-glass mirror previously employed, and the solar image given by it was also larger, and needed no secondary magnifier. The spectrograph itself, it may be stated, magnifies the image about twice.

In order to get spectral images representing central sections of a spot, a very simple guiding arrangement was constructed. This consists of a plane parallel quartz plate, about 1 cm. thick, or of a glass cell with plane parallel sides, containing an absorbing solution, which is placed immediately in front of the slit. This plate or cell is mounted so that it can be inclined, either in a vertical or a horizontal plane, the movement being controlled by a handle conveniently placed near the eye-piece of a telescope, in which may be observed the first or second order spectrum while photographing the third or fourth order. The spot image is first brought as near to the slit as possible by means of the siderostat slow motions; then it is moved horizontally or vertically to any desired position on the slit by inclining the quartz plate or absorbing cell, which thereby moves the image without altering the direction of the rays of light falling on the grating. If long exposures are required, the spot may be kept from wandering in any direction during the exposure by this device, but for short exposures it is merely required to place the spot correctly on the slit.

The image-rotating device described in the Memoirs of the Kodaikanal Observatory, Vol. I, part 1, was also used. This consists of a large total-reflection prism, mounted on a horizontal axis, and with its hypotenuse face in a vertical plane. The light falls normally on one side of the face, and is totally reflected twice, emerging from the other side of the face ; it is then reflected on to the slit by a second mirror. The rotation of the prism through any angle produces a rotation of the image on the slit plate of twice that angle. It is used to adjust the image so that the slit may bisect a spot in a direction passing through the centre of the sun's disk, or in a direction at right angles to that. I call these sections " radial " and " tangential " respectively.

With these arrangements a beautiful series of spectra was secured at Kodaikanal of the spot which crossed the visible disk of the sun between March 29 and April 12, 1915, in latitude 21° north,[1] the sky conditions during that period proving very favourable in the early morning hours. (See plate III.)

Of the series of plates obtained eleven have been measured, and the others have been carefully examined under the micrometer microscope. The spectra obtained with a radial slit show larger displacements than have been measured in any spot spectra hitherto photographed. Assuming the displacement to represent motion in the line of sight, parallel to the surface of the sun, the largest mean velocity measured for a number of lines of intensity 1 is 3·52 km/sec., on the west side of the spot ; and for two of the lines, viz., 4726·3 and 4729·2 it amounts to 4 km/sec. On the east side the movement is smaller, being only about half as much as on the west. Most of the spectra taken with a tangent slit also show some evidence of motion, which will be discussed later. The point I wish to emphasize here is 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 ; it is not considered that this particular spot was an unusually active one. The exposure times in this series of spectra range from five to thirty seconds for lantern plates, varying with the distance of the spot from the centre of the disk, and with the region of spectrum. For Wratten " Instantaneous " plates, exposures could be reduced to a fraction of a second, but the contrast in these is less satisfactory than in the lantern plates, partly, I believe, from a defect in the grating, which, notwithstanding the extreme faintness of the third order ghosts, gives less good contrast than the Rowland grating, in which the ghosts are more obtrusive in emission spectra.

The spectra were measured by means of a single straight spider thread in the micrometer eye-piece. This was placed as nearly parallel as possible to the spectrum lines on either side of the spot image. Each line selected for measurement was then bisected at four points as seen in the field of the microscope as follows :—

(1) In the undisturbed photosphere spectrum, above the spot band.
(2) Near the outer limit of the upper penumbra.
(3) Near the outer limit of the lower penumbra.
(4) In the undisturbed photosphere spectrum, below the spot band.

The positions (1) and (4) were measured at the same distance above and below the centre of the spot, and the penumbral measures are referred to the mean of the photosphere measures, to eliminate a systematic error which would arise from a want of parallelism between the spider thread and the spectrum lines. As the thread was adjusted so as to give very small differences between the upper and lower photosphere measures, any outstanding error due to the small distance of the penumbræ from the centre of the spot became insignificant, and not worth the labour of correcting. This error would tend to increase the shifts on one side of the spot relative to those on the other, but would not affect the sum of the shifts. As is the usual practice, the spectra were each measured twice, viz., with the red end of the spectrum to the right, and left, respectively. This method of measuring is the simplest for obtaining separate values of the displacements for the east and west edges of spots ; but more accurate values of the relative shifts of the different lines could be obtained by the positive on negative method, or by the method of juxtaposing the two opposite edges of the spot, as described by Dr. St. John.[2]

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[1] Greenwich No. 7223.
[2] Astrophysical Journal XXXVII, 322.

For most of the images, the lines selected for measurement were limited to well defined Fe lines of intensities ranging from 0 to 6 of Rowland's scale ; but in the plate giving the largest shifts some lines of Ni, Cr, and Ti were also measured.

Radial movements in east and west penumbræ.—I will discuss first the series of spectra obtained with the radial slit, and therefore giving the displacements due to the radial movement of the spot vapours. In the following tables are given the observed velocities in the line of sight derived from the displacements of the Fe lines, in a spot which crossed the meridian on April 4–5, 1915, in north latitude 20°·7. Table I represents a plate exposed on April 3, with the spot east of the central meridian, and this is followed in tables II and III by measures of spectra photographed on April 6 and 7, when the spot was west of the central meridian. On the 6th, three radial sections of the spot were photographed (table II a, b, and c). a and b are each through the wider part of the umbra, but as they show systematic differences of velocity, they are treated separately. c represents a parallel section through a narrower part of the umbra.

MOVEMENTS IN PENUMBRÆ DERIVED FROM FE LINES GROUPED ACCORDING TO INTENSITY.

TABLE I.

Date 1915, April 3.
Latitude of Spot (on central meridian) + 20°·7.
Central Distance (sun's radius = 1) 0·589 east.
Slit radial.

λ	Intensity.	East Penumbra km/sec.	West Penumbra km/sec.	λ	Intensity.	East Penumbra km/sec.	West Penumbra km/sec.
4695·402	1	+ 1·70	− 1·15	4690·317	4	+ 1·38	− 1·20
4701·231	1	+ 1·65	− 0·64	4703·131	4	+ 1·55	− 1·19
4705·641	0	+ 1·10	− 1·46	4728·732	4	+ 1·18	− 1·18
4711·665	0	+ 2·00	− 0·95	4731·637	4	+ 1·35	− 0·85
4726·327	0	+ 1·71	− 1·85	4733·779	4	+ 0·85	− 0·54
4729·207	1	+ 1·48	− 1·08	4745·992	4	+ 1·33	− 0·98
				4748·325	4	+ 1·20	− 1·33
Means for intensity 0 and 1.		+ 1·61	− 1·19	4773·007	4	+ 0·73	− 0·61
4721·179	2	+ 1·31	− 1·18	Means for intensity 4		+ 1·19	− 0·98
4757·771	2	+ 1·28	− 1·23	4707·457	5	+ 1·10	− 1·05
Means for intensity 2		+ 1·29	− 1·20	4736·963	6	+ 0·18	− 0·62
4709·271	3	+ 1·32	− 1·14	Means for intensities 5 and 6.		+ 0·64	− 0·83
4710·471	3	+ 0·77	− 0·82				
4736·031	3	+ 1·21	− 1·03				
4741·718	3	+ 1·34	− 0·62				
4744·573	3	+ 1·69	− 1·07				
Means for intensity 3		+ 1·26	− 0·94				

Reduced to horizontal movement, the mean velocities are :—

Line intensity.	East Penumbra km/sec.	West Penumbra km/sec.
0 and 1	+ 2·73	− 2·02
2	+ 2·19	− 2·04
3	+ 2·14	− 1·59
4	+ 2·02	− 1·66
5 and 6	+ 1·09	− 1·41

TABLE IIa.

Date 1915, April 6.
Latitude of Spot (on central meridian) 20°·7.
Central Distance (sun's radius = 1) 0·513 west.
Slit radial through wider part of umbra.

λ	Intensity	East Penumbra km/sec.	West Penumbra km/sec	λ	Intensity	East Penumbra km/sec	West Penumbra km/sec.
4615·743	1	− 0·66	+ 1·33	4607·831	4	− 0·43	+ 1·09
4620·693	1	− 0·38	+ 1·56	4618·971	4	− 0·66	+ 1·13
4634·895	1	− 0·61	+ 2·06	4630·306	4	− 0·33	+ 0·98
4662·149	1	− 0·69	+ 1·28	4638·193	4	− 0·37	+ 0·93
Means for intensity 1		− 0·58	+ 1·56	4643·645	4	− 0·42	+ 1·35
4587·308	2	− 0·53	+ 1·11	4647·617	4	− 0·18	+ 0·74
4595·540	2	− 0·43	+ 1·11	Means for intensity 4		− 0·40	+ 1·04
4604·735	2	− 0·38	+ 1·43	4603·126	6	− 0·24	+ 0·81
4636·027	2	− 0·56	+ 1·21	4625·227	5	− 0·28	+ 1·13
Means for intensity 2		− 0·47	+ 1·21	4629·521	6	− 0·56	+ 1·22
4598·303	3	− 0·43	+ 0·87	4637·685	5	− 0·28	+ 0·99
4602·183	3	− 0·29	+ 1·10	4679·027	6	− 0·45	+ 0·95
4613·386	3	− 0·47	+ 1·00	Means for intensity 5 and 6		− 0·36	+ 1·04
4619·468	3	− 0·19	+ 1·19				
4669·354	3	− 0·46	+ 1·13				
Means for intensity 3		− 0·37	+ 1·13				

Reduced to horizontal movement, the mean velocities are :—

Line intensity	East Penumbra km/sec	West Penumbra km/sec.
1	− 1·13	+ 3·04
2	− 0·92	+ 2·36
3	− 0·72	+ 2·20
4	− 0·78	+ 2·02
5 and 6	− 0·70	+ 2·02

TABLE IIb.

The same date and spot as in Table IIa, but another plate in a different region of spectrum.

Slit radial, through wider part of umbra.

λ	Intensity	East Penumbra km/sec.	West Penumbra km/sec	λ	Intensity.	East Penumbra km/sec.	West Penumbra km/sec.
4695·042	1	− 0·79	+ 1·53	4688·357	2	− 0·65	+ 1·57
4701·231	1	− 0·55	+ 1·75	4721·179	2	− 0·73	+ 1·95
4705·641	0	− 0·78	+ 1·79	4757·771	2	− 0·84	+ 1·77
4711·665	0	− 0·96	+ 1·69	Means for intensity 2		− 0·74	+ 1·76
4726·327	0	− 1·13	+ 2·03				
4729·207	1	− 0·90	+ 2·07				
Means for intensity 0 and 1		− 0·85	+ 1·81				

λ	Intensity	East penumbra km/sec.	West penumbra km/sec	λ	Intensity.	East penumbra km/sec.	West penumbra km/sec.
4709·271	3	− 0·91	+ 1·46	4690·317	4	− 0·93	+ 1·67
4710·171	3	− 0·46	+ 1·00	4705·131	4	− 1·24	+ 1·47
4736·031	3	− 0·94	+ 1·66	4728·732	4	− 0·58	+ 1·49
4741·718	3	− 0·89	+ 1·34	4731·651	4	− 0·63	+ 2·02
4744·573	3	− 0·94	+ 1·79	4733·779	4	− 0·36	+ 1·17
Means for intensity 3		− 0·83	+ 1·45	4745·992	4	− 0·80	+ 1·69
				4748·325	4	− 1·11	+ 1·73
				4773·007	4	− 1·00	+ 1·09
				Means for intensity 4		− 0·83	+ 1·54
				4707·457	5	− 0·46	+ 1·15
				4736·963	6	− 0·72	+ 0·59
				Means for intensity 5 and 6		− 0·59	+ 0·87

Reduced to horizontal movement, the mean velocities are —

Line intensity	East penumbra km/sec	West penumbra km/sec
0 and 1	− 1·65	+ 3·52
2	− 1·44	+ 3·42
3	− 1·62	+ 2·82
4	− 1·61	+ 3·00
5 and 6	− 1·15	+ 1·69

TABLE IIc.

The same date and spot as in Table IIa and b.
Slit radial, through narrower part of umbra.

λ	Intensity	East penumbra km/sec	West penumbra km/sec.	λ	Intensity.	East penumbra km/sec.	West penumbra km/sec.
4615·743	1	− 0·76	+ 1·85	4584·018	4	− 0·33	+ 0·73
4620·695	1	− 0·52	+ 1·75	4607·831	4	− 0·52	+ 0·95
4634·895	1	− 0·65	+ 1·17	4618·971	4	− 0·80	+ 1·00
4662·149	1	− 0·92	+ 1·19	4630·306	4	− 0·52	+ 1·12
Means for intensity 1		− 0·71	+ 1·49	4638·193	4	− 0·42	+ 1·07
				4643·645	4	− 0·42	+ 1·16
4587·135	2	− 0·63	+ 1·35	4647·617	4	− 0·42	+ 0·70
4595·540	2	− 0·63	+ 1·02	Means for intensity 4		− 0·49	+ 0·96
4601·735	2	− 0·67	+ 1·47	4603·126	6	− 0·43	+ 0·57
4636·027	2	− 0·61	+ 1·45	4625·227	5	− 0·66	+ 1·08
Means for intensity 2		− 0·63	+ 1·32	4629·521	6	− 0·75	+ 1·03
4598·303	3	− 0·43	+ 1·30	4637·685	5	− 0·42	+ 1·12
4602·183	3	− 0·53	+ 1·15	4679·027	6	− 0·41	+ 1·18
4613·386	3	− 0·52	+ 1·76	Means for intensity 5 and 6		− 0·53	+ 1·09
4619·168	3	− 0·43	+ 1·33				
4669·354	3	− 0·73	+ 1·19				
4683·745	3	− 0·58	+ 1·72				
Means for intensity 3		− 0·51	+ 1·46				

Reduced to horizontal movement, the mean velocities are :—

Line intensity	East penumbra km/sec.	West penumbra km/sec.
1	− 1 37	+ 2·90
2	− 1 23	+ 2·57
3	− 1 05	+ 2·26
4	− 0 95	+ 1 86
5 and 6	− 1 03	+ 1·95

TABLE III.

Date—1915 April 7.
Latitude of Spot +20°·7 (on central meridian).
Central Distance (sun's radius = 1) 0·617 west.
Slit radial.

λ	Intensity.	East penumbra km/sec	West penumbra km/sec.	λ	Intensity	East penumbra km/sec.	West penumbra km/sec.
4542 600	1	− 1 06	+ 2·08	4508 455	4	− 0·64	+ 1 48
4545 311	1	− 0 96	+ 2·22	4584·018	4	− 0·61	+ 1 26
4566 693	1	− 0 76	+ 2·47	4607 931	4	− 0 33	+ 1·80
4574 396	1	− 1 23	+ 2·36	4618 971	4	− 1 32	+ 1·70
4615 743	1	− 0 57	+ 2 03	4630 306	4	− 0 42	+ 1 72
4620 693	1	− 1 80	+ 1·83	4638 193	4	− 0·14	+ 1 90
4634 895	1	− 1 07	+ 2 09	4643·645	4	− 0 74	+ 2 13
Means for intensity 1		− 0 92	+ 2·15	4647·617	4	− 0·23	+ 1 29
4560 266	2	− 0 67	+ 2·24	Means for intensity 4		− 0·55	+ 1 66
4574·899	2	− 0 66	+ 1·75				
4587·308	2	− 0 80	+ 1·96	4603·126	6	− 0·48	+ 0 81
4595·540	2	− 1 07	+ 1 49	4625·227	5	− 0·47	+ 1·92
4636 027	2	− 0 70	+ 1 86	4637 685	5	− 0·37	+ 1·77
Means for intensity 2		− 0·78	+ 1·86	Means for intensity 5 and 6.		− 0·44	+ 1·50
4515 508	3	− 0·39	+ 1·82				
4520 397	3	− 0·84	+ 1 82				
4546 129	3	− 0·52	+ 1·50				
4548 024	3	− 0·48	+ 1·44				
4556·063	3	− 0 57	+ 1 87				
4598 303	3	− 0·84	+ 1·53				
4602 183	3	− 0·38	+ 1·42				
4619 468	3	− 0 66	+ 1·65				
4669 354	3	− 0 64	+ 1·68				
4683·745	3	− 0 54	+ 1·89				
Means for intensity 3		− 0 58	+ 1·66				

Reduced to horizontal movement, the mean velocities are :—

Line intensity.	East penumbra km/sec.	West penumbra km/sec.
1	− 1·49	+ 3·48
2	− 1 26	+ 3·02
3	− 0 93	+ 2·69
4	− 0·89	+ 2·69
5 and 6	− 0·71	+ 2·43

It is remarkable that when east of the central meridian the eastern penumbra gives the larger velocity, but when west of the meridian, the velocities are larger in the western penumbra. The largest displacements were thus always found on the limb side of the spot in this series of measures. This may be an accidental circumstance, although the same phenomenon appears on some of my previous measures. It is evidently of importance to measure the shifts on the limb and centre side of a spot separately.

In table IV, I give the mean velocities on each side of the spot, when east, and when west, of the central meridian; from this it is seen that the preponderance of velocity on the limb side of the spot is much more marked when the spot was west than when it was east.

TABLE IV.

—	Line intensity	East Penumbra km/sec	West Penumbra km/sec	—	Line intensity.	East Penumbra km/sec.	West Penumbra km/sec.
Spot east of C M (one set of measures).	0 and 1	+ 2·73	− 2·02	Spot west of C.M. (four sets of measures).	0 and 1	− 1·41	+ 3·23
	2	+ 2·19	− 2·04		2	− 1·21	+ 2·84
	3	+ 2·14	− 1·59		3	− 1·08	+ 2·49
	4	+ 2·02	− 1·66		4	− 1·06	+ 2·39
	5 and 6	+ 1·09	− 1·41		5 and 6	− 0·90	+ 1·98

The velocities found in the penumbræ of spots generally increase with the distance from the centre of radiation, the motion being zero at some point in the umbra, and accelerating outwards.[1] An unsymmetrical spot, therefore, might be expected to give the greater velocities where the penumbra is more extended. On April 3, the widths of penumbræ were approximately 16,000 km. on the east side, and 13,000 km. on the west. As, on this date the velocity at the outer limits is greater on the east side, this is in accordance with the above statement; but on April 6 and 7, when the velocity on the west side is more than twice that on the east, this same inequality persists, and is greater than before, the east penumbra being about 19,000 km. in width, whilst the western penumbra is only 10,000 km. in a radial section.

The displacements at equal distances east and west of the umbra are therefore very unequal on April 6 and 7. This might conceivably be due to a proper motion of the spot as a whole, in a westerly direction. A forward movement equal to 0·9 km/sec would account for the difference of shifts between the east and west penumbræ. If this were the case, there would be a displacement towards red in the lines over the umbra, equivalent to 0·9 km/sec, which apparently there is not. The lines are here too faint for measurement, but as they are distinctly more inclined on the western penumbra than on the eastern, this points to an absence of appreciable shift in the umbra.

The eastern penumbra is much less definitely bounded than the western, and the outlying parts on the east side show no displacement on April 7, the greatest shift being found at a point about 9,000 km. within the outer limits of the penumbra (see fig. 1, page 174). At the point where the motion ceases, there is a slight rift in the penumbra, and it is the outer separating portion which shows no radial movement. This remarkable absence of movement has also been observed previously, when the radial slit has passed through a completely isolated patch of penumbra. It would seem that radial motion does not occur in penumbræ without an umbral centre.

On April 8th the radial slit passed through a completely detached penumbra on the east side and over this the lines are bent in the usual way indicating radial motion; the photoheliograph plate shows however that this penumbra is forming a secondary nucleus and constitutes a small satellite spot.

[1] This acceleration, indicated by the slant of the lines over the penumbræ, is well seen in all the spectra except in the east penumbra on April 6, in the section through the narrow part of the umbra. In this image the line appears to be as much displaced near the umbra as it is near the outer edge of the penumbra.

Another novel and interesting feature in the spectrum of this spot is the bending of the lines on the adjacent photosphere spectrum, clearly indicating movement outside the western penumbra. (See fig. 1. The bending of the lines outside the spot spectrum can also probably be made out in the half-tone reproduction in plate III.) On this side of the spot, the highest velocity occurs, as is normally the case, at the outer edge of the penumbra, where it reaches almost 4 km/sec for some of the weaker lines Immediately beyond this point, on the photosphere outside, the lines assume their normal width, but not their normal position, for they curve sharply back to a point about 8,000 km. outside the penumbra, where they regain their normal wave-lengths Although the radial motion is thus continued with diminishing velocity far outside the penumbra, there is nevertheless, a very marked kink in the line, or change of velocity, at the penumbral limit. For lines of intensity 4, the appearance is as in fig. 1 excepting that the lines over the spot are less dark and their edges much more diffuse than in the woodcut.

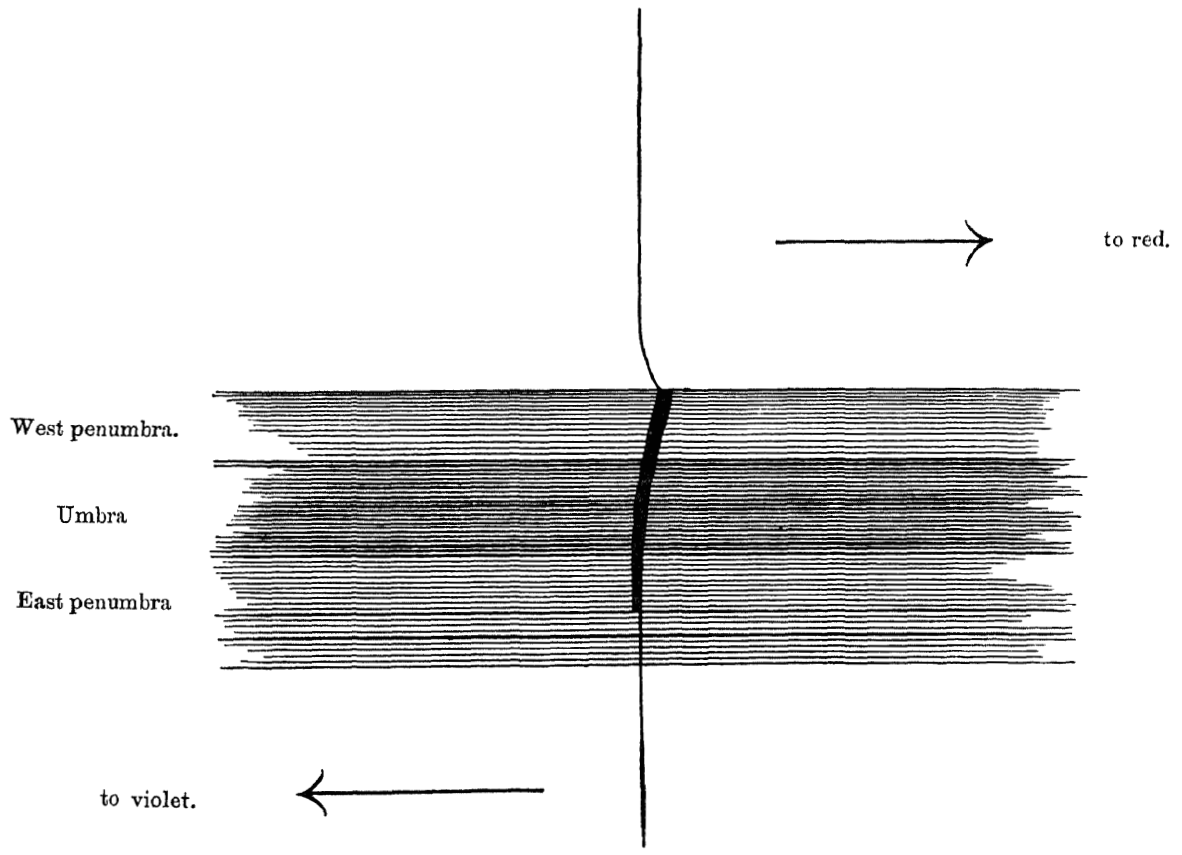

FIG. 1 Course of Fe line crossing spot—April 7, 1915.

Outside the spot, the lines are of normal width right up to the edge of the penumbra, where there is a sudden bend or shoulder. Inside the penumbra, they are in some cases twice the normal width, with a tendency to diffusion in the direction of displacement, indicating velocities still higher than those measured for a portion of the absorbing gas. The shoulder-like bend is best seen in lines of intensity 3 and 4; in weaker lines the curvature outside the penumbra is well seen, but the increase in width at the shoulder is not so evident.

The curvature of the lines is well seen in all the plates taken after the meridian passage of the spot, viz, on April 6, 7, 8 and 9. It is also indicated in the spectra of April 3.

Radial motion in relation to line intensity.—The mean velocities obtained by averaging the results from east and west penumbræ do not vary much on the different dates when spectra of this spot were obtained. I therefore give in table V the mean results for all the five sets of measures detailed in tables I, II and III.

TABLE V.

Mean Velocities of East and West Penumbræ.

Line intensity.	Mean Velocity (5 sets of measures).
0 and 1	2·33 km/sec.
2	2·04 „
3	1·80 „
4	1·75 „
5 and 6	1·42 „

The velocities here shown do not differ materially from those obtained from the earliest radial motion plates measured by me in the year 1909.[1] They are however about 2·7 times larger than those found by St. John for the corresponding line intensities. These are from spectra photographed in the years 1910 and 1911 (see table VII "The Iron Scale" in his paper on "Radial Motion in Sunspots," Astrophysical Journal XXXVII, pages 332—353). This large discrepancy is probably mainly accounted for by the small size of the spots photographed by St. John, which averaged 34″ in diameter on the meridian, or roughly 25,000 km. across the radial section, whereas the spot of April 1915, corrected for foreshortening, was from 44,000 to 48,000 km. across the radial section, excluding the outer portion of the eastern penumbra which showed no motion.

As the velocities at the outer limits of the penumbræ are usually roughly proportional to the diameter of the spot, the spot of April 1915 should give nearly double the velocities found by St. John. My figures in table V may therefore be compared directly with those given in St. John's "Iron scale," which represent the sum of the velocities at the two edges of the spots, and are therefore twice the mean values of east and west penumbræ. The comparison shows a considerable outstanding discrepancy, my figures being about $1\frac{1}{3}$ times larger than St. John's. This may possibly be due to real differences of velocity between the spots concerned, but is more probably the result of diffusion of the spot image on the slit plate, inevitable in the long exposures required in St John's photographs, which were obtained with an autocollimating spectrograph of long focus. This would certainly diminish the apparent shift of the lines.

The relation between the intensity of the lines and the velocity of the radial motion, given in St. John's "Iron scale," is satisfactorily confirmed by my results, as will be seen by dividing my figures by the constant 1·36. The agreement is then very close, although my results are derived from a very limited region of spectrum and small number of lines of each intensity. The correspondence is indeed closer than might have been anticipated, considering the large individual variations, accidental or otherwise, shown in tables I, II and III.

Lines of intensity less than 1 cannot be measured with any approach to accuracy in my plates, excepting in a few cases, where lines of intensity 0 have been included with those of intensity 1.

Among the lines I have measured there are seven enhanced lines of iron. The individual radial motions given by these may be compared in tables II, III and VI with the mean radial motions given by other lines of the same intensity. The lines and their intensities are given below, with a reference to the tables in which they may be found, viz.—

Enhanced Fe lines.	Intensity.	Table.
4508·455	4	III and VI.
4515·508	3	III and VI.
4520·397	3	III and VI.
4522·802	2	VI.
4556·063	3	III and VI.
4584·018	4	III and VI.
4629·521	6	IIa and IIc.

[1] Monthly Notices of the Royal Astronomical Society LXX 223.

According to St. John's measures, "the enhanced lines show smaller radial displacements than the unenhanced lines of the same solar intensities, and would appear to originate at higher levels in and near sunspots."[1] I can find no evidence of any such systematic difference for the above enhanced Fe lines, compared with ordinary Fe lines of the same intensities. These particular lines were, however, not measured by St. John, who appears to have based his conclusions mainly on titanium lines.

In the plates of April 7, in which very large velocities are obtained in the western penumbra, some lines of nickel, chromium, and titanium were also measured, in addition to the Fe lines. Five lines of Ni, eleven lines of Cr and twelve lines of Ti give results which are not sensibly different from the lines of corresponding intensities in the Fe spectrum. In the case of Ti, five lines of intensity 2 give slightly greater mean displacements than the Fe lines of this intensity, and four lines of intensity 3 give displacements almost identical with the Fe lines of intensity 3 in the same region. This is not in agreement with St. John's results, according to which the Ti lines give sensibly smaller displacements than the Fe lines of the same intensity. Although the displacements in these spectra are large, amounting to about 0·035 Å for intensity 2, these results can have but small weight compared with St. John's, which are based on a large number of measures.

Spectrum of Companion Spot.—It is of interest to compare the spectrum of the principal spot, which I will call spot A, with that of a companion spot closely following it, which I will call spot B (see plate III). This developed during the passage of the group across the disc, and on the dates April 6, 7, 8 and 9 spectra of both A and B were obtained. On the 8th, a radial slit passed through both spots, and both are recorded in one wide spectral image. The general appearance of the spectrum of spot B is more normal than that of spot A, for the displacements in the east and west penumbræ are more nearly equal, and there is no displacement observable beyond the limits of the penumbræ on either side. Measures of the displacements show however that, like spot A, the west or limb side yields higher velocities than the east, although the penumbra on the west is narrower than on the east. Details of the measures of the best image obtained on April 7 are given in table VI.

TABLE VI.

Date—1915, April 7.
Latitude of Spot + 16 (on central meridian).
Central distance (sun's radius = 1) 0·496 west.
Slit radial.

λ	Intensity.	East penumbra km/sec.	West penumbra km/sec	λ	Intensity.	East penumbra km/sec.	West penumbra km/sec.
4505·003	1	− 0·99	+ 1·10	4515·508	3	− 0·89	+ 1·19
4529·849	1	− 0·68	+ 1·32	4517·702	3	− 0·79	+ 1·63
4542·600	1	− 1·16	+ 0·97	4520·397	3	− 0·89	+ 0·94
4565·002	0	− 1·09	+ 1·57	4548·024	3	− 0·87	+ 1·30
4566·693	1	− 1·14	+ 1·28	4556·063	3	− 0·96	+ 1·29
4567·046	1	− 1·52	+ 1·56	Means for intensity 3	..	− 0·88	+ 1·27
4574·396	1	− 0·86	+ 1·80	4489·911	4	− 1·00	+ 0·96
4584·900	1	− 0·94	+ 1·40	4508·455	4	− 0·59	+ 1·24
Means for intensity 0 and 1.	.	− 1·05	+ 1·37	4584·018	4	− 0·33	+ 0·66
4490·942	2	− 1·10	+ 1·30	Means for intensity 4	...	− 0·64	+ 0·95
4522·802	2	− 0·63	+ 1·17	4494·738	6	− 1·20	+ 0·85
4531·801	2	− 0·97	+ 1·02	4525·314	5	− 0·44	+ 1·13
4560·266	2	− 0·96	+ 1·53	4531·327	5	− 0·83	+ 0·93
4574·899	2	− 1·00	+ 1·04	Means for intensity 5 and 6.		− 0·82	+ 0·97
Means for intensity 2.	...	− 0·93	+ 1·21				

[1] Radial Motion in Sunspots, II. Astrophysical Journal XXXVII.

Reduced to horizontal movement, the mean velocities are—

Line intensity	East Penumbra km/sec	West Penumbra km/sec	Mean of E. and W. km/sec
0 and 1	− 2·12	+ 2·77	2·44
2	− 1·87	+ 2·14	2·15
3	− 1·78	+ 2·56	2·17
4	− 1·29	+ 1·92	1·60
5 and 6	− 1·65	+ 1·96	1·80

The mean horizontal velocities given in the last column in the last part of the table appear rather larger than in spot A (table V), especially for the lines of intensity 5 and 6, which give slightly larger displacements than lines of intensity 4. It has been mentioned that in the case of spot A a diffusive widening of the lines occurs near the limits of the penumbræ, a diffusion in the direction of displacement only. This is also well seen in some images of spot B. If this is interpreted as a motion effect, it means that near the outer limits of the penumbræ some portions of the absorbing gases develop greater velocities than other portions. The phenomenon is of course involved in the Zeemann widening of the lines, and it tends to make estimates of the displacements uncertain, owing to a want of symmetry. It is for this reason possible that some of my measures of velocity, both in spot A and spot B, are over-estimates in the case of some of the stronger lines. It is possible that the more diffused portion of the strong lines is shown up in stronger contrast than in the case of the weaker lines.

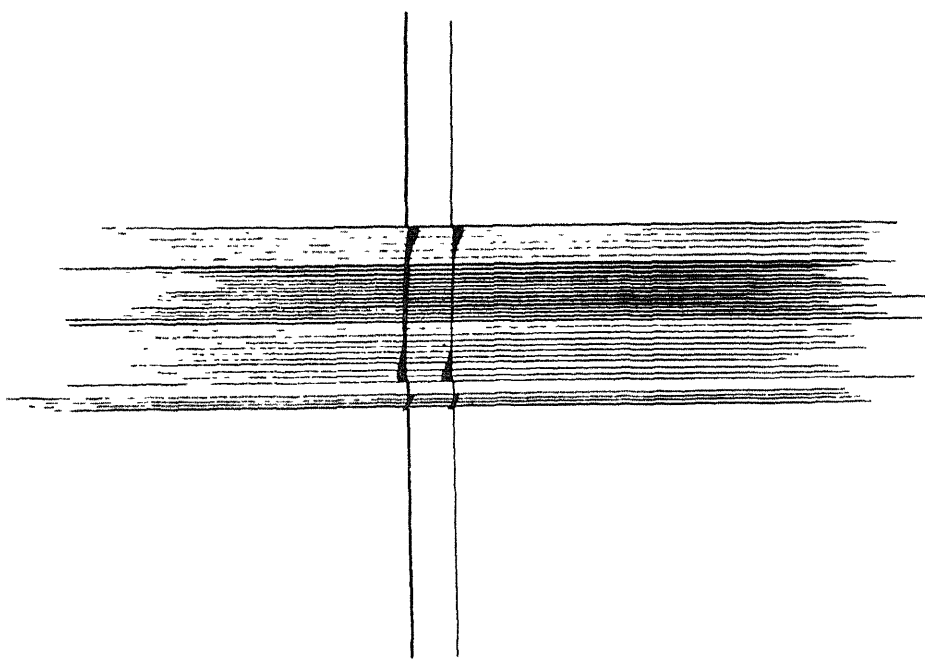

Fig. 2. Diffusive widening of lines near outer edges of penumbræ

This diffusion of the lines in the direction of displacement does not seem to occur in all spots. In these spectra it is found near the outer limits of the penumbræ, a region where the lines are also intensified, so that in observing the spectrum visually one sees little black dots or lumps along the edges of the

penumbræ marking the most displaced portion of the lines, and sharply contrasting with the undisplaced lines outside the penumbræ. This appearance had been observed several times when focussing spot spectra before I had succeeded in photographing it. Fig. 2 is an exaggerated representation of this effect.

Spot B had a double nucleus. On the 6th and 7th of April a rift or bridge, roughly north and south, divided the umbra into an eastern and a western portion, and it is of interest to note that some of the lines of small intensity, notably the chromium line 1571·849, intensity 1, show a slight kink in this rift, indicating that each nucleus was forming an independent centre of radial movement with opposing currents in the rift, tending perhaps to separate the umbræ. At the outer limits of the penumbræ, and especially on the western side, where the displacement is greatest, the kink in the lines indicates a sudden drop in velocity from the maximum value of nearly 3 km/sec. to zero. One cannot say that any trace of the motion shift can be seen beyond the limit of the penumbra. Spot B differs markedly therefore from spot A in this respect, but larger scale photographs and still better definition might of course show a progressive decrease of velocity. I think I am justified in saying, however, that in spot B any progressive decrease of velocity must have been confined to an extremely narrow zone, perhaps not exceeding one-hundredth part of the diameter of the spot.

From the foregoing results, the following brief summary may be made:

(1) The radial motion displacement may be very unequal at equal distances from the umbra of a spot, and the two spots investigated showed larger displacements on the limb side than on the centre side.

(2) Detached penumbræ appear to show no radial movement, except when secondary nuclei are developed in them, forming independent centres of radial motion.

(3) The radial movement may be continued for a considerable distance outside the limits of the penumbræ, or it may stop short at those limits.

(4) There is usually an acceleration of velocity from the umbra to the outer limits of the penumbræ, and then a sudden fall to zero, or to a lesser speed which diminishes to zero at some distance outside the spot.

(5) The radial movement may amount to 1 km/sec. at one edge of the penumbra for lines of intensity 0 and 1 in large spots. The mean radial movement for east and west edges appears to be fairly constant for spots of the same diameter.

(6) There is a tendency to diffusion of the lines in the direction of displacement near the outer limits of the penumbræ in some spots, indicating turbulent motion.

(7) The relation found between line intensity and radial movement for Fe lines agrees with that given by St. John in his "iron scale."

(8) Enhanced lines of iron, and the lines of chromium, nickel, and titanium, in the region of spectrum investigated, do not show any systematic differences compared with ordinary iron lines having the same intensities.

MOVEMENTS AT RIGHT ANGLES TO THE RADIAL MOVEMENT.

The spectra photographed with a tangent slit were measured in the same way as the others. The displacement of the lines is of course very much smaller than with the radial slit, but is still quite obvious in some of the spectra. Interpreting the displacement as a motion parallel to the surface of the sun, the measures show velocities of about 0·5 km/sec. The first plate of the series, representing spot A on April 1, has three images of the spectrum impressed on it, by two slightly different but parallel sections through the umbra. All show a slight displacement to red at the outer limit of the south penumbra, but no appreciable displacement in the north penumbra. The spectrum representing the more westerly section gives a larger displacement than the others. This section passes through a wedge-shaped indentation in the umbra and through an apparently much disturbed region in the penumbra outside it, the displacement at the outer edge of the penumbra is equivalent to 0·6 km/sec. horizontal movement. The measurement in this spectrum of thirteen Fe lines of mean intensity 1·8 is given in table VII.

TABLE VII.

Date—April 1, 1915.
Latitude of Spot + 20° 7 (on central meridian).
Central distance (sun's radius = 1) 0·825 east.
Slit tangent.

λ	Intensity	North Penumbra km/sec.	South Penumbra km/sec.
5273·339	3	− 0·32	+ 0·42
5273·558	2	0·00	+ 0·50
5288·705	2	+ 0·01	+ 0·27
5292·762	0	+ 0·44	+ 0·69
5294·134	0	+ 0·13	+ 0·88
5295·485	0	+ 0·30	+ 0·25
5307·541	3	− 0·06	+ 0·41
5315·252	1	+ 0·15	+ 0·48
5321·293	2	− 0·02	+ 0·61
5322·227	3	− 0·08	− 0·39
5326·331	1	+ 0·10	+ 1·05
5330·179	2	+ 0·13	+ 0·58
5333·089	4	+ 0·04	+ 0·42
Means		+ 0·06	+ 0·53

Reduced to horizontal movement, the velocities are—

North Penumbra.	South Penumbra
+0·07 km/sec.	+ 0·64 km/sec.

This is the only plate obtained in the green region of the spectrum; and although the exposures were of thirty seconds' duration, the spectra are under-exposed. A "Royal Standard Ortho" plate was used, and a solution of flavasine to cut out the fourth order violet. The definition of the penumbræ is good. On the same day, two hours later, two more spectra with a tangent slit were obtained: these include the region 4686 to 4785. The definition of the penumbræ is not so good as in the earlier plates, as the quality of the seeing at 10 a.m. is always inferior to that at 8 a.m. These spectra represent a section slightly to the east of the centre of the spot, and not passing through the wedge-shaped indentation. In both spectra there is a very slight shift to red over the whole spot, including probably the umbra itself, although the lines are here under-exposed and difficult to measure.

It would seem that the displacement first observed at the southern limit of the south penumbra in all spectra photographed at 8 a.m. had spread over the entire spot at 10 a.m. It cannot represent a rotational movement in the spot, since both sides are moving in the same direction. The displacement is of course relative to the photosphere a short distance outside the spot, and may be interpreted in different ways: there may be currents outside the spot, moving in a westerly direction, or the spot as a whole may be drifting eastwards, or the movement may be normal to the surface, and indicate a general descent of the gases over the spot, or finally there may be a combination of these movements. If the movement is parallel to the sun's surface, it amounts to 0·46 km/sec; but if it is normal to the surface, it indicates a descending movement amounting to 0·65 km/sec. The mean velocities in the line of sight from fourteen Fe lines of average intensity 3·1 are as follows:—

	North Penumbra.	South Penumbra.
Observed velocities	+ 0·37 km/sec.	+ 0·39 km/sec.
Reduced to horizontal movement	+ 0·45 km/sec.	+ 0·47 km/sec.

On the next day, with the spot at 0·711 east from the centre, the displacement is all in the north penumbra, and is still towards red. As the spot was then about 45° from the centre of the disc, the deduced velocities

parallel to or normal to the surface are the same, and amount to as much as 0·9 km/sec. The mean velocities from twelve Fe lines of average intensity 3·0 are as follows :—

	North Penumbra.	South Penumbra.
Observed velocities	+ 0·65 km/sec.	− 0·07 km/sec.
Reduced to horizontal movement	+ 0·91 km/sec.	− 0·10 km/sec.

The tangent slit spectra of spot A obtained near the eastern limb indicate therefore considerable movements of recession of an irregular character, and little or no movement of approach. They give no evidence of rotation of the gases at the level of the reversing layer, and it is not possible to say whether the movements are parallel to or normal to the solar surface.

After the meridian passage, and when the spot was nearing the western limb on April 9, tangent spectra yield a different result. The lantern plate spectra were not measured, as they give poor definition of the penumbræ, but a Wratten "Instantaneous" plate exposed for ¼ second in the region 4450 gives a distinct image of the spot, and in this there is evidence which may be interpreted as a rotation of gases over the spot, since opposite sides of the spot give opposite movements. There is a very distinct displacement to violet at about the middle of the south penumbra, the lines over the outer portion being undisplaced. There was a small satellite spot on the south edge of the penumbra, and the point where the displacement ceases appears to be the junction between the penumbra of the satellite spot and the main penumbra. On the north side, the displacement towards red is distinct, but less in amount than the violet shift on the south side. The other tangent slit spectra taken on this date show the same displacements, but less distinctly.

The measures of thirteen Fe lines of mean intensity 1·7 give the following results :—

	North Penumbra	South Penumbra.
Observed velocities	+ 0·56 km/sec.	− 0·76 km/sec.
Reduced to horizontal movement	+ 0·65 km/sec.	− 0·88 km/sec.

The spot diameter measured from the points of greatest shift was 41,000 km. Assuming a continuous rotation movement, at a mean speed of 0·77 km/sec, at the outer edge, the entire spot would complete a rotation in about 46 hours, the north penumbra moving towards west, that is a clockwise rotation. This is not the direction found by Prof. Hale from the magnetic polarity of spots. He states that "in bi-polar groups of low latitude, the preceding spot-vortices rotate counter-clockwise in the northern hemisphere."[1] The spot was the preceding member of the group, approximately in latitude + 21°.

It is very doubtful whether these line displacements really indicate rotation of the gases over the spot. There is no evidence of rotation in the shape of the spot itself and its outlying satellites, as shown in our photoheliograph plates. The umbra of the preceding spot is of rather irregular form on April 6 and 7 (see plate III, figs. 1 and 2), but it assumes an elliptical shape with less marked irregularities as the west limb is approached. This is mainly due to foreshortening, the long axis of the ellipse being parallel to the limb. There is, however, a wide indentation on the north-east side of the umbra which occupies the same position on the dates April 6, 7, 8 and 9. The penumbra is greatly extended on the north side of the spot, as well as to the south-east : but throughout the interval of four days there is no change in the position angle of these outlying parts of the spot. If the gases of the reversing layer above the spot share in the rotational movement of the underlying spot vortex, one would expect to find evidence of rotation in the markings of the spot itself, which should turn half round in a day, from the evidence of the line-shifts. But the spot-markings do not show this rotation, although the *radial* movement of the overlying vapours is most distinctly indicated in the radial structure of the penumbral filaments.

From the whole of the evidence so far obtained with the tangent slit, I conclude that irregular movements at right angles to the radial movement may occur in the penumbræ of spots, and that if a rotation movement exists in some spots, it is not a constant and regular feature, as is the radial movement.

THE OBSERVATORY, KASHMIR,
27th June 1916.

J. EVERSHED,
Director, Kodaikanal and Madras Observatories.

[1] Annual Report of Mount Wilson Solar Observatory for 1915.

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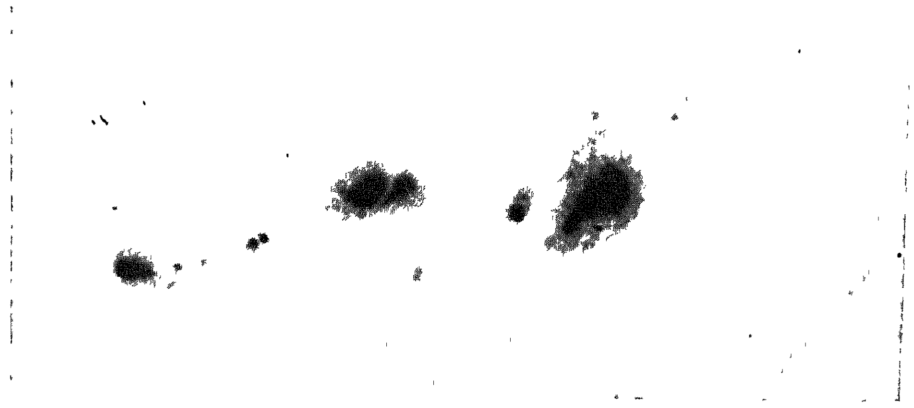


Fig. 1

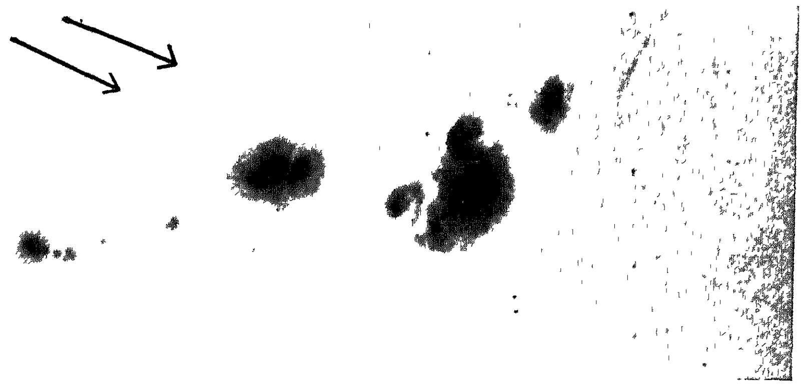
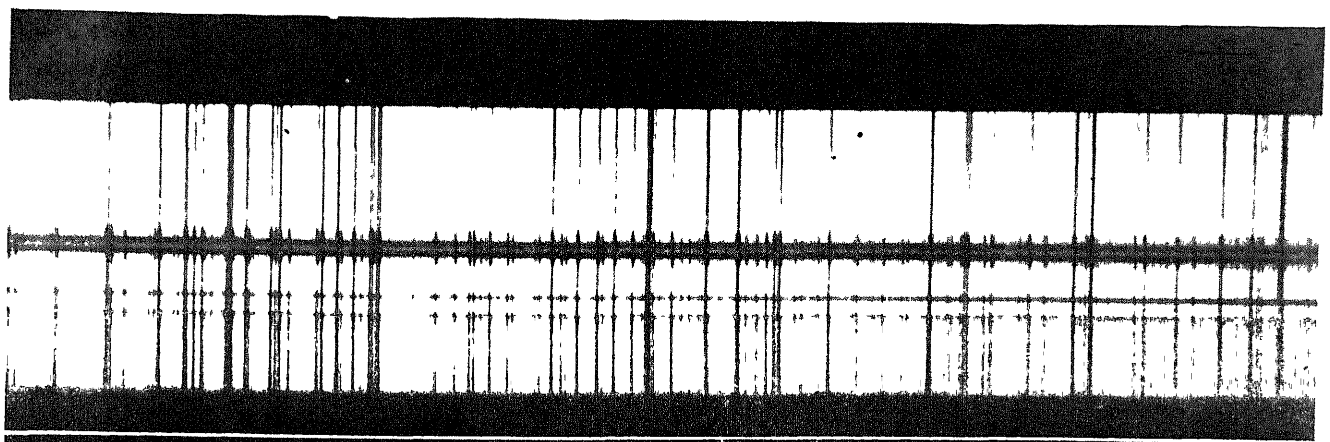


Fig. 2



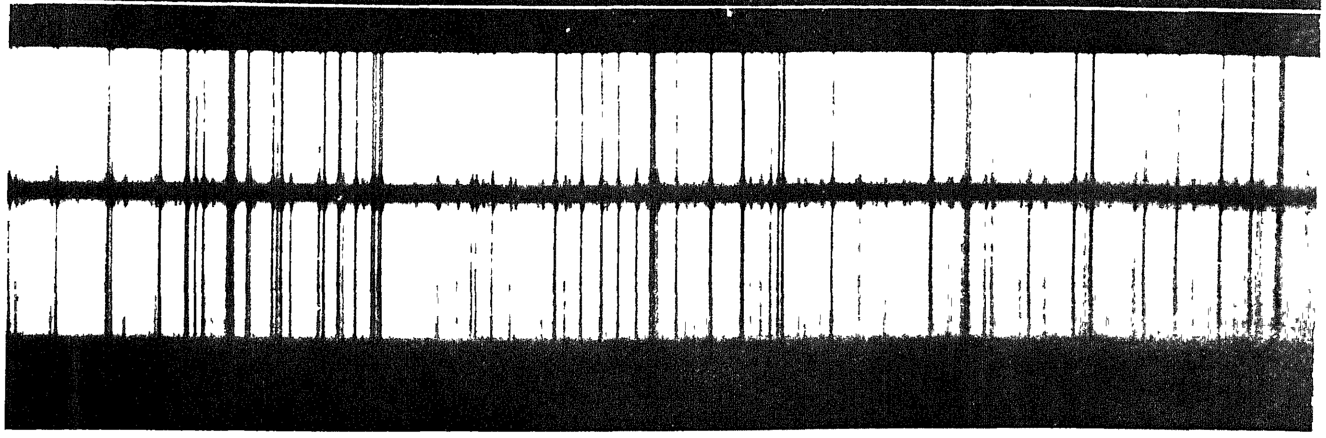


Fig. 1. Spot group 1915, April 6th, $7^{h.}$ 57^{m} I. S. T

„ 2. „ „ „ April 7th, 8^{h} 02^{m} I. S. T

„ 3. Spectrum of following spot } April 7th, Region 4520 – 4580. Slit radial.

„ 4. „ „ preceding spot }

The arrow marks in Fig. 2 indicate the direction of the radial slit in Figs. 3 and 4.