ON THE PROBABLE EXISTENCE OF A MAGNETIC FIELD IN SUN-SPOTS[1]

By GEORGE E. HALE

The discovery of vortices surrounding sun-spots, which resulted from the use of the hydrogen line *Hα*, for solar photography with spectroheliograph,[2] disclosed possibilities of research not previously foreseen. Photographs taken daily on Mount Wilson with this line suggest that all sun-spots are vortices, and provide material for a discussion of spot theories which will soon be undertaken. Revealing, as they do, the existence of definite currents and whirls in the solar atmosphere, they afford the requisite means of testing the operation in the sun of certain physical laws previously applied only to terrestrial phenomena. The present paper describes an attempt to enter one of the new fields of research opened by this recent work with the spectroheliograph.

ELECTRIC CONVECTION

In 1876 Rowland discovered that an electrically charged ebonite disk, when set into rapid rotation, produced a magnetic field, capable of deflecting a magnetic needle suspended just above the disk.[3] It thus appeared, in accordance with Maxwell's anticipation, that a rapidly moving charged body gives rise to just such effects as are caused by an electric current flowing through a wire. Rowland's whirling disk therefore corresponds to a wire helix, within which a magnetic field is produced when a current is passed through it.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 30. A preliminary note bearing the title "Solar Vortices and the Zeeman Effect," was sent to *Nature* for publication June 30. A brief abstract of this note appeared in *Nature* for August 20, together with a very interesting paper by Professor Zeeman, who was kind enough to examine some copies of my photographs, taken with the rhomb and Nicol in June. My own note was subsequently printed in *Publications of the Astronomical Society of the Pacific*, **20**, 220, 1908.

[2] Hale, "Solar Vortices," *Contributions from the Mount Wilson Solar Observatory*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[3] Rowland, "On the Magnetic Effect of Electric Convection," *American Journal of Science* (3), **15**, 30, 1878.

Recent studies of the discharge of electricity in gases prove that gases and vapors, when ionized by one of several means, contain electrically charged particles. Moreover, at high temperatures carbon and many other elements which occur in the sun emit negatively charged corpuscles in great numbers; the complementary positively charged particles must also be present, more or less completely separated from the negative corpuscles.[1] Thus electromagnetic disturbances on a vast scale may result from the rapid motions of charged particles produced by eruptions or other solar disturbances.

Soon after the discovery of the vortices associated with sun-spots, it occurred to me that if a preponderance of positive or negative ions or corpuscles could be supposed to exist in the rapidly revolving gases, a magnetic field, analogous to that observed by Rowland in the laboratory, should be the result. An equal number of positive and negative ions, when whirled in a vortex, would produce no resultant field,[2] since the effect of the positive charges would exactly offset that of the negative charges. But Thomson's statement regarding the possible copious emission of corpuscles by the photosphere, and the tendency of negative ions to separate themselves, by their greater velocity, from positive ions, led to the belief that the conditions necessary for the production of a magnetic field might be realized in the solar vortices.

Thanks to Zeeman's discovery of the effect of magnetism on radiation it appeared that the detection of such a magnetic field should offer no great difficulty, provided it were sufficiently intense. When a luminous vapor is placed between the poles of a powerful magnet the lines of its spectrum, if observed along the lines of force, appear in most cases as doublets, having components circularly polarized in opposite directions. The distance between the components of a given doublet is directly proportional to the strength of the field. As different lines in the spectrum of the same element are affected in different degree, it follows that in a field of moderate strength many of the lines may be simply widened, while others, which are exceptionally sensitive, may be separated into doublets.

[1] J. J. Thomson, *Conduction of Electricity through Gases*, p. 165.

[2] Unless separated by centrifugal force, as suggested by Professor Nichols.

THE SUN-SPOT SPECTRUM

It has long been known that the spectrum of a sun-spot differs from the ordinary solar spectrum in several particulars. If, for example, we examine the iron lines in a spot, we find that some of them are more intense than in the solar spectrum, while others are weaker. Again, we perceive that many of the spot lines are widened, and that the degree of widening varies for different lines. Finally, if the observations are made with an instrument of high dispersion, it will be seen that some of the iron lines, which are single in the solar spectrum, are double in the spot spectrum. Such double lines were first seen by Young in 1892 with a large spectroscope attached to the 23-inch Princeton refractor. Walter M. Mitchell, who subsequently observed them with the same instrument, described the doublets as "reversals," which they closely resemble. Mitchell's papers contain a valuable series of observations of these "reversals" and other sun-spot phenomena.[1]

Our previous investigations in this field on Mount Wilson may be summarized as follows:

1. The application of photography to the study of sun-spot spectra. A Littrow or auto-collimating spectrograph of 18 feet (5.5 m) focal length, used with the Snow telescope, gave good results, and permitted a great number of spot lines and bands, not previously known, to be recorded.[2] On the completion of the tower telescope last autumn, these observations were continued with a vertical spectrograph of 30 feet (9.1 m) focal length.[3] Although the only grating available for work in the higher orders is a 4-inch (10 cm) Rowland, having 14,438 lines to the inch (567 to the mm), employed in my experiments in photographing sun-spot spectra at the Kenwood and Yerkes

[1] Walter M. Mitchell, "Reversals in the Spectra of Sun-Spots," *Astrophysical Journal*, **19**, 357, 1904; "Researches in the Sun-Spot Spectrum, Region F to *a*," *ibid.*, **22**, 4, 1905; "Results of Solar Observations at Princeton, 1905–1906," *ibid.*, **24**, 78, 1906.

[2] Hale and Adams, "Photographic Observations of the Spectra of Sun-Spots," *Contributions from the Mount Wilson Solar Observatory*, No. 5; *Astrophysical Journal*, **23**, 11, 1906.

[3] Hale, "The Tower Telescope of the Mount Wilson Solar Observatory," *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

Observatories,[1] the results secured with this instrument are very satisfactory, greatly surpassing those obtained with the 18-foot spectrograph. They give the first photographic records of the "reversals" or doublets seen visually by Young and Mitchell, and reveal thousands of faint lines beyond the reach of visual observation.

2. The preparation of a photographic map of the sun-spot spectrum and a catalogue of all the lines. A preliminary map, consisting of 26 sections of 100 Ångströms each, covering the region λ 4600–7200, was prepared last year by Mr. Ellerman from negatives made with the 18-foot spectrograph, and supplied to visual observers taking part in the sun-spot work of the International Solar Union. A much better map, to be made from negatives obtained with the tower telescope and 30-foot spectrograph, will be ready, it is hoped, within a year. The catalogue of lines, which involves a great amount of measurement for the determination of wave-lengths, is well advanced, and one section has been published by Mr. Adams.[2]

3. The identification of the numerous lines which constitute the flutings in the spot spectrum. Photographs of the spectra of titanium oxide, magnesium hydride, and calcium hydride,[3] made in our laboratory by Dr. Olmsted, have furnished the material for this purpose. The measurement of the lines in these flutings is well advanced.

4. The interpretation of the change of the relative intensity of lines observed in passing from the solar spectrum to the spot spectrum. Investigations on the spectra of iron, manganese, chromium, titanium, vanadium, and other metals conspicuous in spots, made with the arc, spark, and flame, indicated that this change is due to a reduction of the temperature of the spot vapors.[4] Subsequent work with a new

[1] Hale, "Solar Research at the Yerkes Observatory," *Astrophysical Journal*, **16**, 211, 1902.

[2] Adams, "Preliminary Catalogue of Lines Affected in Sun-Spots, Region λ 4000 to λ 4500," *Contributions from the Mount Wilson Solar Observatory*, No. 22; *Astrophysical Journal*, **27**, 45, 1908.

[3] Olmsted, "Sun-Spot Bands Which Appear in the Spectrum of a Calcium Arc Burning in the Presence of Hydrogen," *Contributions from the Mount Wilson Solar Observatory*, No. 21; *Astrophysical Journal*, **27**, 66, 1908.

[4] Hale, Adams, and Gale, "Preliminary Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Mount Wilson Solar Observatory*, No. 11; *Astrophysical Journal*, **24**, 185, 1906; Hale and Adams, "Second Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Mount Wilson Solar Observatory*, No. 15; *Astrophysical Journal*, **25**, 75, 1907.

electric furnace by Dr. King,[1] the details of which have not yet been published, seems to leave little doubt that this explanation is correct. It is supported by the presence in the spot of compounds which appear to be dissociated at the higher temperature outside the spot, and by the resemblance of spot spectra to the spectra of red stars.[2]

While our investigations have thus furnished a plausible explanation of some of the characteristic phenomena of sun-spot spectra, the widening of lines and the presence of doublets are among the remaining peculiarities that demanded consideration. As we have seen, however, these very peculiarities are precisely what would be expected if a magnetic field were present. Prompted by the theoretical considerations outlined above, and encouraged by their apparent agreement with the facts of observation, I decided to test the components of the spot doublets for evidences of circular polarization and to seek for other indications of the Zeeman effect.

METHOD OF OBSERVATION

The tower telescope forms an image of the sun, about 6.7 inches (17 cm) in diameter, on the slit of a vertical spectrograph, of 30 feet focal length. This instrument, to which reference has already been made, stands in a well with concrete walls, the grating being about 26½ feet (8 m) below the surface of the ground. The temperature at the bottom of the well is so constant that exposures of any desired length may be given, without danger of a shift of the lines resulting from expansion or contraction of the grating. A Fresnel rhomb and Nicol prism[3] are mounted above the slit, so that the light of the solar image passes through them. If the doublets in spots are produced by a magnetic field, the light of their components, circularly polarized in opposite directions, should be transformed by the rhomb into two

[1] King, "An Electric Furnace for Spectroscopic Investigations, with Results for the Spectra of Titanium and Vanadium," *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[2] Hale and Adams, "Sun-Spot Lines in the Spectra of Red Stars," *Contributions from the Mount Wilson Solar Observatory*, No. 8; *Astrophysical Journal*, **23**, 400, 1906; Adams, "Sun-Spot Lines in the Spectrum of *Arcturus*," *Contributions from the Mount Wilson Solar Observatory*, No. 12; *Astrophysical Journal*, **24**, 69, 1906.

[3] Obtained for this purpose in 1905, when the idea of searching for the Zeeman effect in sun-spots had already occurred to me. A visual test of the spot lines for plane polarization, made with the 18-foot spectrograph in 1906, before we had photographed the doublets, gave negative results.

plane polarized rays, differing 90° in phase. Thus, in a certain position of the Nicol, the light from the red component should be transmitted and that of the violet component cut off. When rotated 90° in azimuth, the Nicol should transmit the violet component and cut off the red component. Complete extinction of either component is hardly to be expected, because the light from the spot does not, in general, come exactly along the lines of force, and the doublets may therefore exhibit some traces of elliptical polarization. Moreover, the beam of sunlight undergoes two reflections on the silvered surfaces of the coelostat and second mirrors of the tower telescope, where elliptical polarization must again be introduced.[1] By setting the rhomb at the proper angle, the latter effect, which is not very large, can be almost wholly eliminated, but the former may play some part, even when the spot is at the center of the sun.

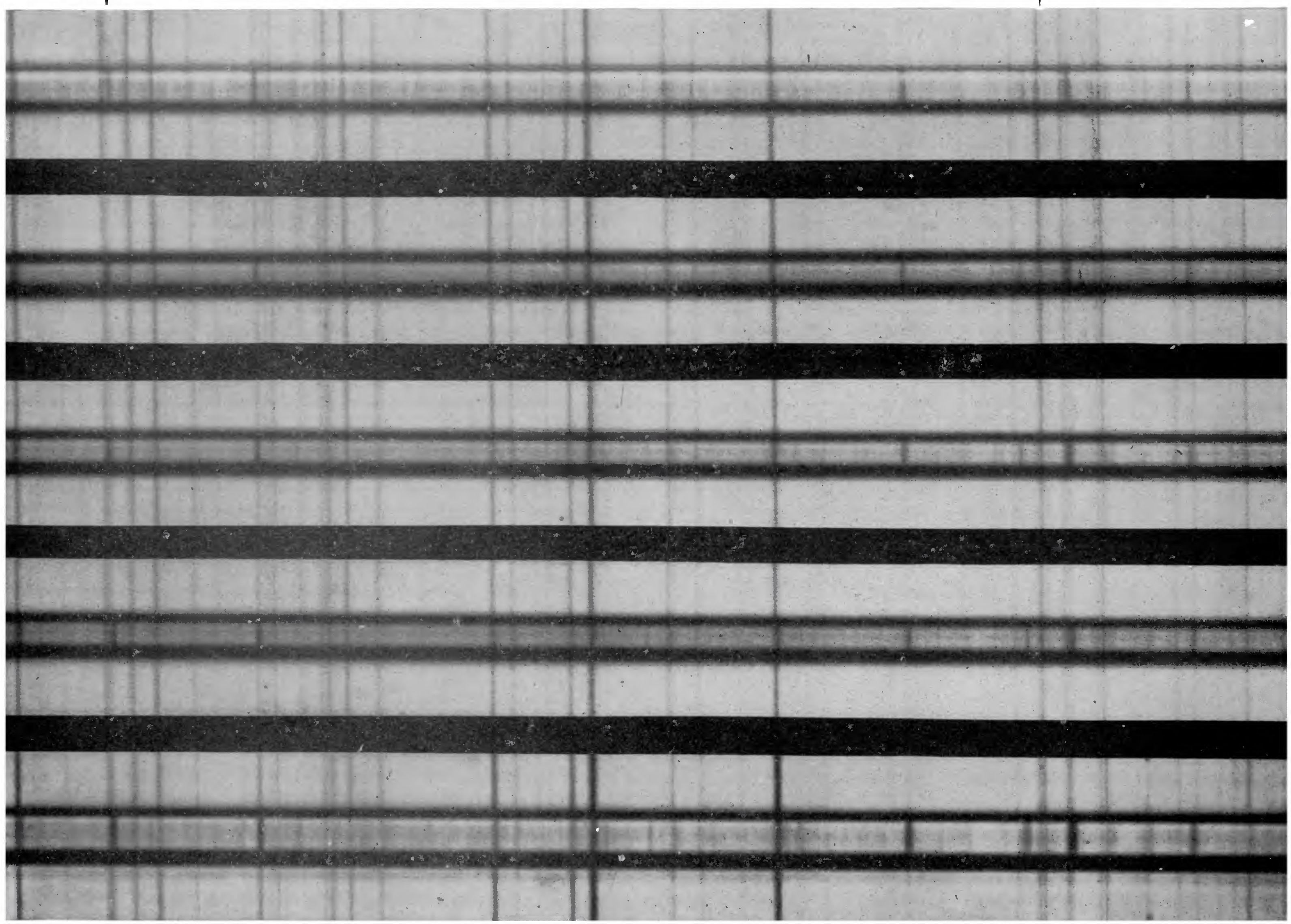
The light of the spot, after transmission through the rhomb and Nicol, comes to a focus in the plane of the slit. While photographing the spot spectrum the slit is covered except at its central part, where a portion corresponding in length (from 1 to 2 mm) to the diameter of the umbra, receives the light. During the exposure, which may continue from a few minutes to over an hour, the image of the umbra is kept as nearly as possible central on the slit, any irregularities in the motion of the driving-clock being corrected by the observer. As the exposure for the spot spectrum is from five to twenty times as long as for the solar spectrum, it is evident that care must be taken to prevent light from regions outside the spot from entering the slit.

For a comparison spectrum sunlight is used, generally from a point in the solar image a short distance away from the spot, where none of the characteristic spot phenomena appear. During the exposure, that part of the slit which previously received the light of the umbra is covered, and sunlight admitted on either side. The light of the comparison spectrum passes through the rhomb and Nicol, both of which occupy the same positions as in the case of the spot. Care is taken to see that the grating is fully illuminated, both for the spot and comparison spectra, in all positions of the Nicol.

[1] A study of the elliptical polarization of these mirrors has been made by Dr. St. John.

PLATE XXVI

5918.77 5940.87



(1) (2) (3) (4) (5)

(1) Southern spot, showing red components of doublets. Nicol 29° W. (2) One umbra of northern spot, showing violet components of doublets. Nicol 29° W. (3) Other umbra of northern spot, showing violet components of doublets. Nicol 29° W. (4) Some umbra of northern spot, showing red components of doublets. Nicol 61° E. (5) Spot spectrum without rhomb or Nicol, showing both components of doublets. Scale: 1 Ångström=6 mm.

CIRCULAR POLARIZATION ALONG THE LINES OF FORCE

My first observations were made on June 24, in the second order of the grating, but the results were not conclusive. On June 25 I obtained some good photographs, in the third order, of the region λ 6000–6200, using Seed's "Process" plates, sensitized for the red by Wallace's three-dye formula.[1] These clearly showed a reversal of the relative intensities of the components of spot doublets when the Nicol was turned through an angle of 90°. Moreover, many of the widened lines were shifted in position by rotation of the Nicol, indicating that light from the edges of these lines is circularly polarized in opposite directions. The displacements of the widened lines appeared to be precisely similar in character to those detected by Zeeman in his first observations of radiation in a magnetic field.

A series of photographs, made with the Nicol set at various angles, soon showed the two positions giving the maximum effect. At these positions the weaker components of the strongest doublets are not always completely cut off, but their intensities are greatly reduced. Sometimes hardly a trace of the weaker component remains, as may be seen in the case of the vanadium doublet at λ 5940.87 (Plate XXVI). In this plate No. 5 shows the doublet in the ordinary spot spectrum, photographed without the rhomb and Nicol. No. 4, from a photograph (T 190) made with the Nicol set at 61° E., shows only the red component of the doublet. No. 3 illustrates the effect of turning the Nicol 90°: only the violet component remains. Other spot lines in these photographs change in a similar way.

Photographs like these seemed to leave no doubt that the components of the spot doublets are circularly polarized in opposite directions. Since the only known means of transforming a single line into such a doublet is a strong magnetic field, it appeared probable that a sun-spot contains such a field, and that the widening and doubling of the lines in the spot spectrum result from this cause. But much remained to be done before the proof could be regarded as complete.

In the first place, it was necessary to make sure that the displacement of the lines other than doublets was not due to instrumental causes, such as a change in the illumination of the grating produced by rotating the Nicol. As already stated, care was always taken to

[1] *Astrophysical Journal*, **26**, 299, 1907.

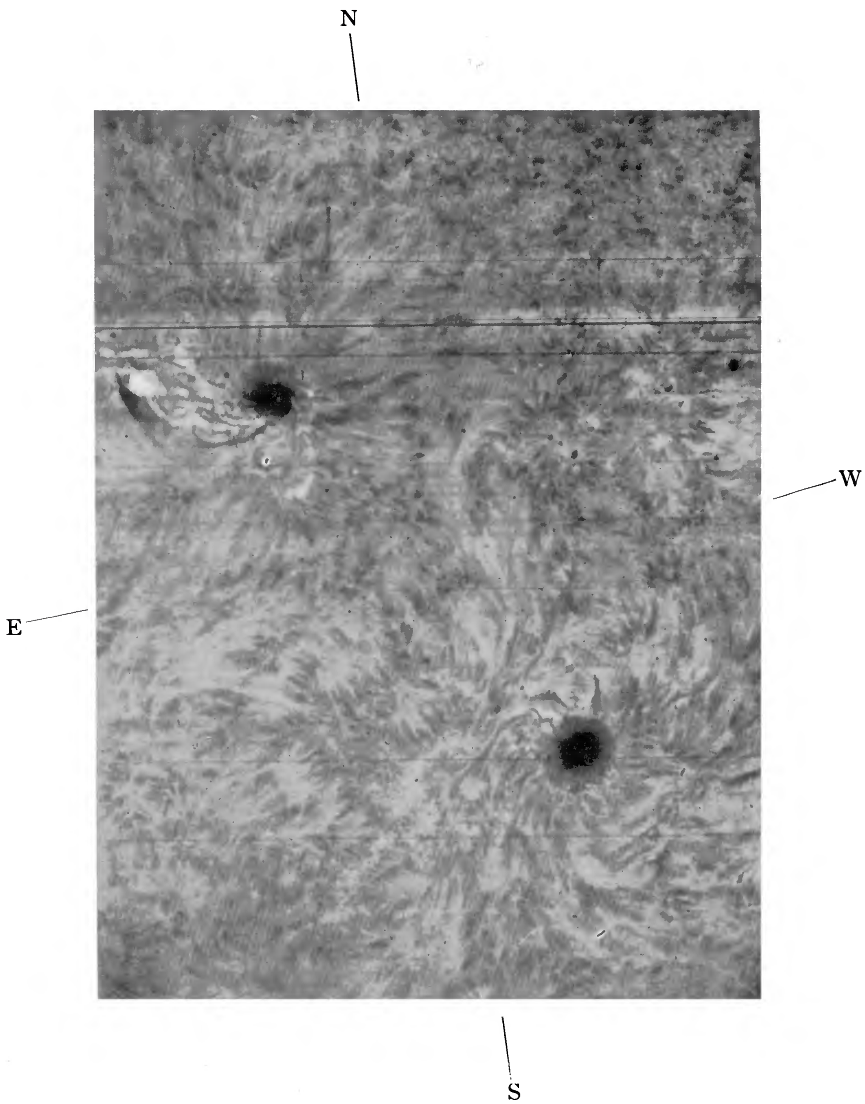
see that the ruled surface was filled with light before making an exposure. Moreover, the magnitude of the displacement was much greater for some lines than for others, and the fact that the shifts were determined with respect to lines of the solar spectrum, whose light had traversed almost the same path as that of the spot in rhomb and Nicol, seemed to leave little room for doubt as to their true character. However, a rigorous test could be applied. The spot spectrum, as well as the solar comparison spectrum, is crossed by lines due to the absorption of water vapor and other gases in the earth's atmosphere. If a change of illumination due to the rotation of the Nicol were concerned, these lines should be displaced from their normal positions. But no such shifts were observed. Furthermore, it is known that the lines of most flutings are not affected by a magnetic field. Accordingly, the cyanogen fluting at λ 3883 was photographed in the spot spectrum, with the Nicol set in two positions 90° apart. Three lines in this fluting, which I have measured on negative T 132, made in the fourth order, show a mean displacement of 0.0004 Ångströms, with respect to the corresponding lines of the solar comparison spectrum. This quantity is well within the error of measurement.[1] We may therefore conclude that the Nicol displaces only those lines which show polarization phenomena.

While measuring this plate, and others taken in the more refrangible part of the spot spectrum, it was found that few of the lines in this region show large shifts. A group of doublets was encountered near λ 4400, the components of which are circularly polarized in opposite directions. In general, however, the shifts produced by rotating the Nicol decrease from the red toward the violet end of the spectrum.

Since this preliminary work I have made over two hundred photographs of spot spectra with polarizing apparatus before the slit. In addition to this collection of plates, numerous photographs of spot spectra, some taken with polarizing apparatus by Dr. St. John, and others made without Nicol or rhomb by Mr. Adams and myself, are available for study. These have been used for the investigation described in the following pages.

[1] The head and several lines of the titanium oxide fluting at λ 5598, which have since been measured by Mr. Adams, also show no displacement when the Nicol is rotated.

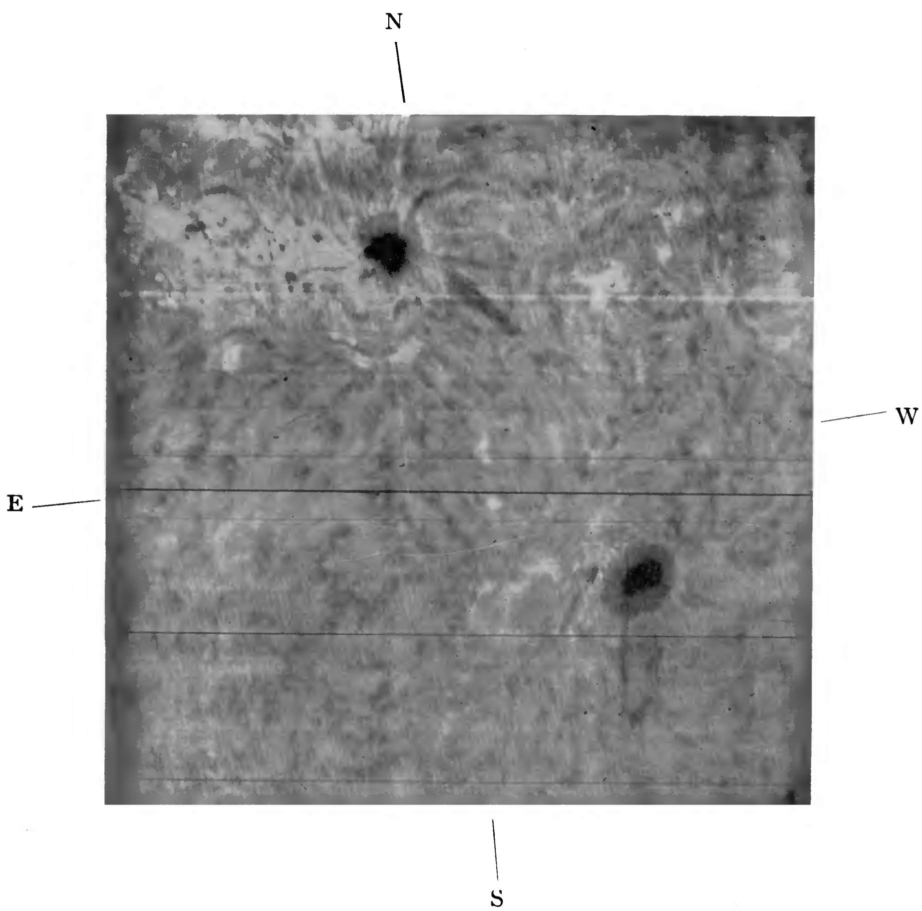
PLATE XXVII



SUN-SPOTS AND HYDROGEN FLOCCULI, SHOWING RIGHT- AND LEFT-HANDED VORTICES

1908, September 9, $6^h\ 20^m$ A. M. Scale: Sun's Diameter=0.3 Meter

PLATE XXVIII



SUN-SPOTS AND HYDROGEN FLOCCULI, SHOWING RIGHT- AND LEFT-HANDED VORTICES

1908, September 7, 6^{h} 20^{m} A. M. Scale: Sun's Diameter=0.3 Meter

REVERSED POLARITIES OF RIGHT- AND LEFT-HANDED VORTICES

A second test, which also bears upon the hypothesis that the field is produced by the revolution of electrically charged particles in the spot-vortex, may now be described. If a Nicol is set so as to cut off the violet component of a doublet observed along the lines of force of a magnetic field, reversal of the current will cause the red component to disappear and the violet component to become visible. Reversal of the direction of the current in a magnet corresponds to reversal of the direction of revolution in a solar vortex. If it could be shown, by an independent method, that in two sun-spot vortices the charged particles are revolving in opposite directions, the red components of the doublets should appear in the spectrum of one spot, and the violet components in that of the other, the position of the rhomb and Nicol remaining unchanged.

Fortunately the spectroheliograph plates indicate the direction of revolution in the solar vortices. The vortices are constantly changing in appearance, and the stream lines are not always clearly defined. Plates XXVII and XXVIII are reproduced from photographs of the sun made by Mr. Ellerman with the 5-foot spectroheliograph on September 9 and 10. They show two spots, one in the northern, the other in the southern hemisphere, with vortices indicating revolution in opposite directions, if we may judge from the curvature of the stream lines.[1] Portions of the spectra of these spots, photographed by myself on September 9, are reproduced in Plate XXVI. No. 1 shows the spectrum of the southern spot, in which the direction of revolution was clockwise, taken with the Nicol set at 29° W. Only the red components of the doublets appear. The northern spot, in which the revolution was counter-clockwise, was then photographed (2). Although the Nicol and rhomb remained in the same position as before, the red components of the doublets are now cut off, while the violet ones are visible. During this exposure the slit was kept on the western umbra of the northern spot, which was divided into two parts by a bridge (not shown in the reproductions). Another exposure, with Nicol and rhomb as before, was then made on the eastern umbra of the same spot (3), with results similar to those obtained for the western umbra. For the final exposure (4) the slit was kept on the eastern

[1] Right- and left-handed vortices have also been found in the same hemisphere.

umbra of the northern spot, and the Nicol rotated 90°. As was to be expected, the red components were brought into view, and the violet components extinguished. This spectrum is therefore precisely similar to that of the southern spot, which was taken with the Nicol in the reverse position.

This result has been confirmed by other photographs, which indicate that the direction of the displacement always depends upon the direction of the revolution in the vortex. If this relation is found by future observations to hold generally, we may conclude that the field is always produced by the revolution of particles carrying charges of like sign.

PLANE POLARIZATION ACROSS THE LINES OF FORCE

So far we have confined our attention to polarization phenomena observed along the lines of force. But it is well known that the doublets are, in general, transformed into triplets, when observed in a magnetic field at right angles to the lines of force. The components of the triplets are plane polarized, the central line in a plane at right angles to the plane of polarization of the side components. It should be possible to detect similar phenomena in spot spectra, if they are produced in a magnetic field.

It naturally happens that these spectra are most commonly observed when the spots are not very far removed from the center of the sun, because foreshortening near the limb reduces the umbra to a narrow strip difficult to keep on the slit. This may partially explain why our photographs of spot spectra, taken without polarization apparatus, show the doublets without a trace of a central component. But it does not account for the failure of the central line to appear in the spectra of spots well removed from the center. It is true that a few triplets occur in all of our spot spectra, such as λ 5781.97, λ 6064.85, and λ 6173.55. But these I have regarded as probable examples of an exceptional type of lines, observed in the laboratory as triplets along the lines of force. Mitchell records certain cases in which many spot doublets were seen as triplets,[1] but he also notes the existence of doublets in the spectra of spots near the limb.[2] In

[1] *Astrophysical Journal*, **24**, 80, 1906.

[2] *Ibid.*, **19**, 357, 1906.

PLATE XXIX

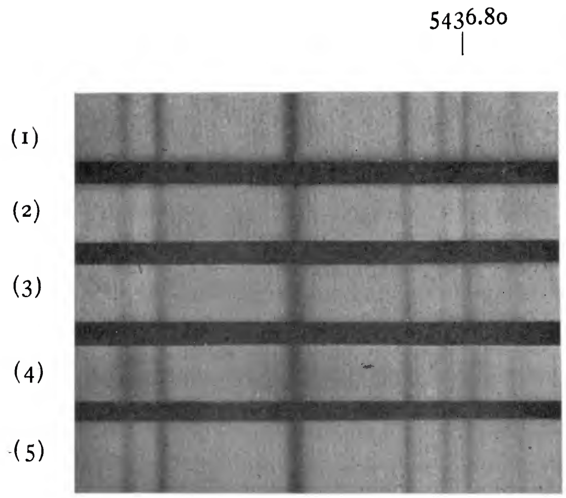


FIG. 1.—(1) and (5) Solar spectrum. (2) Spectrum of a spot near limb, Nicol 60° E. (3) Sp ctrum of a spot near limb, Nicol 60° W. (4) Spectrum of a spot near center, without rhomb or Nicol. Scale: 1 Ångström=6 mm.

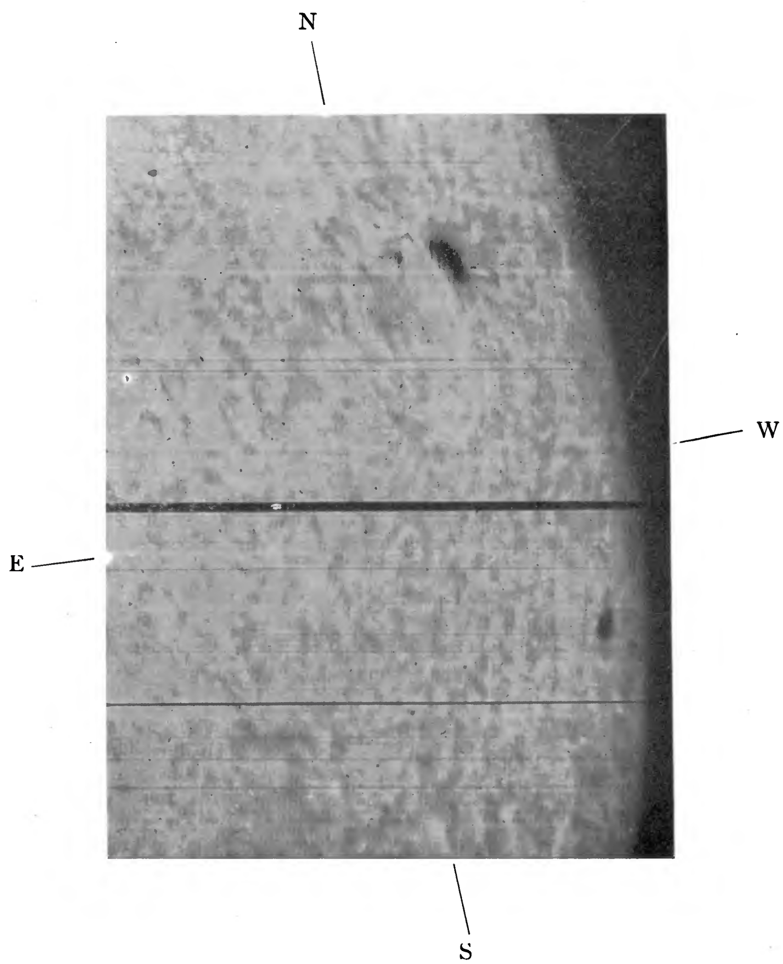


FIG. 2.—Spots near western limb, in which plane polarization of lines was observed.

1908, Sept. 14, $7^h\ 05^m$ A. M. Scale: Sun's Diameter=0.3 Meter.

one interesting observation described and illustrated by Mitchell, the lines appeared double across the umbra and one side of the penumbra, while on the other side of the penumbra they changed into triplets.[1] Since the beginning of my work on the Zeeman effect in the sun, there have been few opportunities to observe the spectra of spots near the limb. These I have utilized, not in attempting to photograph the triplets (which will be tried later), but in testing the polarization phenomena of the spot lines.

The rhomb was removed, and the Nicol employed alone. At right angles to the lines of force the Nicol, when in a certain position, should cut off the outer components of a triplet or the edges of a widened line. In another position, 90° distant, the central component should be extinguished, and the outer components or edges transmitted. Thus, in the second case, lines which are not too diffuse should be photographed as doublets, while in the first case the central component should appear alone.

Plate XXIX reproduces some photographs of a spot near the west limb, made on September 14. The seeing was poor, and neither the $H\alpha$ image nor the spectra are sharply defined. In Fig. 1, Plate XXIX, (1) and (5) represent the solar spectrum; (2) the spot spectrum, photographed with the Nicol set at 60° E.; (3) the spot spectrum, with Nicol set at 60° W.; (4) the same region of another spot spectrum, photographed near center of sun without Nicol. At 60° E. the Nicol cuts out the central line, while at 60° W. it transmits this line and cuts off the side components. Other settings of the Nicol gave the following results, which appear on the same negative (T 200): 90° E., single; 30° E., double; 0°, single, but wide; 30° W., single, but wide. Other photographs, made in this and other regions of the spectrum, gave similar results, the lines being narrow in some positions of the Nicol and wide in others. Only one case of undoubted doubling of the lines has been found. The short time available for work, under favorable atmospheric conditions, when a sufficiently large spot was near the limb, prevented the observations from being carried farther.

LABORATORY TESTS

If the widened lines and doublets in spot spectra are produced by a magnetic field, an equal degree of widening and an equal separation

[1] *Ibid.*, **24**, 80, 1906.

of the components of doublets should be found in the laboratory when the same lines are observed in a field of equal strength. As the necessary apparatus was fortunately available, the work was at once undertaken in our Pasadena laboratory by Dr. King. A brilliant spark is produced by a high potential transformer between electrodes supported in the field of a large Du Bois magnet. The light, passing through the pierced pole-pieces, falls on a lens, which forms an image of the spark on the slit of a vertical spectrograph, after reflection on a mirror mounted at an angle of 45° above the slit. This spectrograph, which is precisely similar to the 30-foot spectrograph used with the tower telescope, also stands in a constant temperature well, with the slit about three feet above the floor of the laboratory.[1] It may be used as an instrument of 30 feet focal length, or, as in the present case, a 5-inch (13 cm) objective of 13 feet (4 m) focal length, with a 5-inch plane grating, having 14,438 lines to the inch (567 to the mm), can be swung into the axis of collimation 13 feet below the slit. With this shorter focal length the dispersion in the second or third order of the grating is amply sufficient for the present purpose.

If all of the doublets observed in spot spectra could be photographed in the laboratory, it would be easy to make a satisfactory comparison. Unfortunately, however, most of these lines are very faint in the spark, and as the great majority of them occur in the less refrangible part of the spectrum, exposures of from fifteen to twenty hours are sometimes required to bring out even the stronger doublets. The results hitherto obtained for the iron doublets are brought together in the following table. I am indebted to Mr. Adams for

TABLE I

IRON DOUBLETS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{5.1}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda,\ \text{Spark}}{\Delta\lambda,\ \text{Spot}}$
6213.14	0.703	0.138	0.136	−0.002	5.2
6301.72	0.737	0.144	0.138	−0.006	5.3
6302.71	1.230	0.241	0.252	+0.011	4.9
6337.05	0.895	0.175	0.172	−0.003	5.2

[1] Hale, "The Pasadena Laboratory of the Mount Wilson Solar Observatory," *Contributions from the Mount Wilson Solar Observatory*, No. 27; *Astrophysical Journal*, **28**, 244, 1908.

these measures and for many of the others given in this paper. Miss Burwell and Miss Wickham have also assisted in the measurement of the spot and spark photographs.

The first column gives the wave-length of the doublet; the second, the separation in Ångströms of the components, observed along the lines of force in a field of about 15,000 gausses;[1] the third, the quantity given in column 2 divided by 5.1; the fourth, the separation of the components observed in the spot spectrum; the fifth, the residuals obtained by substracting the quantities in the third column from those in the fourth; the last column gives the ratio of the separation in the spark, for a field of about 15,000 gausses, to the observed separation in the spot. The mean value of this ratio, 5.1, gives an approximate measure of the strength of the field in spots, which comes out about 2900 gausses.

The agreement between the spot and laboratory results is so close that it can hardly be the result of chance. But when we come to the case of titanium, observed in the laboratory in a field of about 12,500 gausses, we find a very different condition of affairs.

TABLE II

TITANIUM DOUBLETS

Wave-Length	Δλ, Spark	Δλ, Spark / 5.1	Δλ, Spot	δ	Δλ, Spark / Δλ, Spot
5903.56	0.732	0.144	0.086	−0.058	8.5
5938.04	0.737	0.145	0.080	−0.065	9.2
6064.85	0.876	0.172	0.184	+0.012	4.8
6303.98	0.493	0.097	0.093	−0.004	5.3
6312.46	0.615	0.121	0.091	−0.030	6.8

If we use the factor 5.1 employed in the case of iron, we find that two of these doublets, λ 6064.85 and λ 6303.98, agree closely in spot and spark. In some of our spot photographs λ 6064.85 appears to be a triplet, though the components are not clearly separated. With the rhomb and Nicol a faint central component persists when either the red or the violet component is cut off. It is possible that this central line is due to some substance other than titanium in the spot, but it

[1] This value of the field strength may be in error by 1000 gausses, because of the disturbing effect of the iron electrodes.

is certainly very nearly in the position of the solar titanium line.[1] λ 6312.46 gives a residual of 0.03 Ångströms, which exceeds the error of measurement. The other doublets, λ 5903.56 and λ 5938.04, show in the spot spectrum but little more than one-half the separation that would be expected on the assumption that the strength of the field is the same for all of these lines.

On consideration it will be seen, however, that the separation of the doublets must depend, in some degree, on the distribution of the absorbing vapor in the solar atmosphere, and on the coefficient of absorption of the particular line employed. A striking instance of this kind, affecting lines of the same series, is illustrated in the case of hydrogen, described in a previous paper.[2] Although the $H\delta$ line extends to the upper part of the chromosphere and prominences, the mean level represented by its absorption is much lower than that given by $H\alpha$. The consequence is that $H\alpha$ enables us to photograph the solar vortices, the characteristic stream lines of which do not appear at the lower $H\delta$ level. Similarly, if the intensity of a given titanium line falls off rapidly, the level represented by this line may be comparatively low. If, on the other hand, its intensity curve is of such a form as to indicate that the absorption at higher elevations plays an important part, the mean level represented by the line may be considerably higher than in the previous case. To settle this question we must know: (1) The range of elevation in the spot of the vapors of iron, titanium, and other elements; (2) the intensities of the lines of these elements at different levels; (3) the rate at which the strength of the field decreases upward.

In the absence of information regarding the first two points, we may inquire as to the probable relative behavior of titanium, iron, and other elements if the distribution of the vapors at different levels were the same as in the chromosphere. From a discussion of a large number of photographs of the flash spectrum, made by different observers at several eclipses, Jewell has compiled a table showing the heights above the sun's limb attained by various lines in

[1] It is conceivable that under conditions analogous to those that give rise to the H_3 and K_3 lines, a doublet might be produced within the strong magnetic field of the spot, and a single line, at the center of the doublet, by the absorption of the vapor at a high level, where the field strength is low.

[2] *Solar Vortices*, p. 3.

the blue and violet.[1] The heights for titanium range from 100 miles (160 km) for λ 4466.0 to 3500 miles (5640 km) for λ 4466.7, while certain strong enhanced lines in the ultra-violet reach elevations of 6000 or 8000 miles (9660 or 12,880 km). For iron the minimum height is 200 miles (320 km) for λ 4482.4 and the maximum 1000 miles (1610 km) for λ 4584.0. Chromium ranges from 100 miles for λ 4280.2 to 1200 miles (1930 km) for λ 4275.0; manganese from "100 miles or more" for λ 4451.8 to "800 miles (1290 km) or more" for λ 4030.9; vanadium from 100 miles for λ 4390.1 to 200 miles for λ 4379.4. It thus appears that the range in level represented by the titanium lines is much greater than for the lines of iron, chromium, manganese, and vanadium. If the vapors were similarly distributed in spots, the maximum strength of field indicated by the titanium lines should therefore correspond with the maximum value for iron, but some titanium lines, produced by absorption at higher mean levels, should give lower field strengths. Chromium should agree more nearly with iron. Vanadium, if the less refrangible lines reach no greater elevations, should give closely accordant (maximum) values for the field strength. It will perhaps be possible, with the aid of the 30-foot spectrograph, to determine the relative levels in the chromosphere attained by most of the lines in question, but it is a much more difficult matter to do this for sun-spots. I hope, however, that our new spectroheliograph of 30-feet focal length may throw some light on this subject.

It is evident that these considerations will have no bearing on the present problem, unless the field strength decreases very rapidly upward in spots. That this probably occurs is shown by the fact that the D lines of sodium and the *b* lines of magnesium are usually but slightly affected in the spot spectrum,[2] and are displaced through a very small distance when the Nicol is rotated. Thus, at the level represented by these lines, which attain elevations in the chromosphere probably not exceeding 5000 miles, the field strength is reduced to a small fraction of its maximum value.

[1] "Total Solar Eclipses of May 28, 1900, and May 17, 1901," *Publications of the U. S. Naval Observatory*, Second Series, Vol. IV, Appendix I.

[2] Except for the strengthening of the wings, which may be produced by some cause other than a magnetic field.

The following doublets have been measured in the spectrum of chromium:

TABLE III

CHROMIUM DOUBLETS

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{4.9}$	Δλ, Spot	δ	$\frac{\Delta\lambda,\ \text{Spark}}{\Delta\lambda,\ \text{Spot}}$
5304.36	0.636	0.130	0.188	+0.058	3.4
5387.16	0.676	0.138	0.085	−0.043	8.0
5713.00	0.610	0.124	0.161	+0.037	3.7
5781.40	0.755	0.154	0.121	−0.033	6.2
5781.97	0.922	0.188	0.212	+0.024	4.3
5783.29	0.772	0.158	0.137	−0.021	5.6
5784.08	0.720	0.147	0.121	−0.026	6.0
5785.19	0.707	0.144	0.137	−0.007	5.1

In photographing these lines in the spark, the strength of the field was 12,500 gausses. The strength of the field in spots, as indicated by the mean separation of the chromium doublets, is therefore 2600 gausses.

The above tables comprise all of the doublets hitherto observed both in spots and in our laboratory. It was at first hoped that the shifts of lines, on photographs of the spot spectrum made with the rhomb and Nicol, would serve as satisfactory data for comparison with laboratory results. But when the small magnitudes of these shifts, and the wide differences in the character of the lines were taken into account, it appeared that comparisons based on such data could have but little weight.

When a line is clearly resolved into a doublet, rotation of the Nicol cuts off the right-handed or left-handed light, and produces a shift equal to the separation of the components. But when the strength of the field is only sufficient to widen a line, that portion of the widened line where the right-handed and left-handed components overlap is composed of ordinary unpolarized light, not affected by rhomb or Nicol. If the components are narrow, this region may also be narrow. But if they are broad, only the outer edges of the components will be cut off when the Nicol is rotated.

If a magnetic field is the principal cause of the widening of lines in spots, their widths should be roughly proportional to the separation of the components of the corresponding doublets observed in a field of equal strength. Bearing in mind the differences in the character of the lines, and the probable effect of variations in the mean level of absorption, we can hardly expect a very close agreement. But some evidences of relationship should appear, if a magnetic field is present. In the following tables the widths of various iron lines are compared with the separations of their components in the spark. To facilitate the comparison, the distances between the centers of the components, photographed in a field of about 15,000 gausses, are divided by 2.9, which reduces them to approximate equality with the widths in spots.

TABLE IV

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{2.9}$	Width in Spots	δ
6136.19	0.38	0.13	0.15	+0.02
6137.92	0.50	0.17	0.16	−0.01
6191.78	0.43	0.15	0.14	−0.01
6219.49	0.59	0.20	0.23	+0.03
6246.54	0.67	0.23	0.24	+0.01
6252.77	0.45	0.16	0.15	−0.01
6265.35	0.55	0.19	0.20	+0.01
6315.52	0.59	0.20	0.16	−0.04 Enhanced line
6318.24	0.40	0.14	0.14	0.00
6335.55	0.55	0.19	0.20	+0.01
6393.82	0.46	0.16	0.18	+0.02
6400.22	0.58	0.20	0.22	+0.02
6411.86	0.56	0.19	0.17	−0.02
6417.13	0.69	0.24	0.15	−0.09 Enhanced line
6420.17	0.57	0.20	0.19	−0.01
6421.57	0.64	0.22	0.18	−0.04
6431.07	0.54	0.19	0.19	0.00
6456.60	0.55	0.19	0.22	+0.03 Enhanced line
6495.21	0.54	0.19	0.18	−0.01

The exceptionally large residuals of the enhanced lines may be due to the fact that the weakening of these lines in spots makes them very difficult to measure. But it is perhaps possible that another cause may account for the negative sign of most of their residuals in Tables IV and VI. Assume that in the lower part of spots the field is most intense and the reduction of temperature most marked. In consequence of the reduced temperature, the enhanced lines are greatly weakened. Hence an unusually large proportion of the absorption which gives rise to these lines may occur at greater elevations, where

TABLE V

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	Δλ, Spark	Δλ, Spark / 2.9	Width in Spots	δ
5083.58	0.41	0.14	0.15	+0.01
5098.88	0.42	0.14	0.13	−0.01
5107.62	0.25	0.09	0.11	+0.02
5107.82	single*		0.14	
5110.57	0.45	0.15	0.17	+0.02
5123.90	single		0.09	
5125.30	0.41	0.14	0.09	−0.05
5127.53	0.51	0.18	0.15	−0.03
5137.56	0.45	0.15	0.13	−0.02
5139.43	0.56	0.19	0.16	−0.03
5139.64	0.51	0.18	0.15	−0.03
5143.11	0.42	0.14	0.11	−0.03
5162.45	0.47	0.16	0.14	−0.02
5167.68	0.35	0.12	0.12	0.00
5171.78	0.39	0.13	0.15	+0.02
5191.63	0.57	0.20	0.18	−0.02
5192.52	0.56	0.19	0.17	−0.02
5195.11	0.33	0.11	0.14	+0.03
5198.89	single		0.10	
5208.78	0.48	0.16	0.14	−0.02
5215.35	0.45	0.15	0.15	0.00
5216.44	0.23	0.08	0.12	+0.04
5217.55	0.47	0.16	0.15	−0.01
5227.04	0.47	0.16	0.19	+0.03
5227.36	0.32	0.11	0.15	+0.04
5230.03	0.50	0.17	0.15	−0.02
5233.12	0.38	0.13	0.14	+0.01
5242.66	0.29	0.10	0.11	+0.01
5250.82	0.49	0.17	0.14	−0.03
5263.49	0.47	0.16	0.13	−0.03
5266.74	0.38	0.13	0.14	+0.01
5269.72	0.39	0.13	0.15	+0.02
5273.56	0.53	0.18	0.11	−0.07
5276.17	0.31	0.11	0.12	+0.01
5281.97	0.44	0.15	0.11	−0.04
5283.80	0.49	0.17	0.14	−0.03
5302.48	0.48	0.17	0.17	0.00
5316.79	0.32	0.11	0.11	0.00 Enhanced line
5324.37	0.48	0.16	0.16	0.00
5328.24	0.37	0.13	0.17	+0.04
5328.70	0.49	0.17	0.13	−0.04
5340.12	0.48	0.16	0.16	0.00
5365.07	0.30	0.10	0.10	0.00
5367.67	0.31	0.11	0.12	+0.01
5370.17	0.36	0.12	0.12	0.00
5371.73	0.33	0.11	0.16	+0.05
5383.58	0.37	0.13	0.13	0.00
5393.38	0.52	0.18	0.18	0.00
5397.34	0.48	0.16	0.20	+0.04
5400.71	0.42	0.14	0.11	−0.03

* "Single" in these tables does not mean that the line is not affected by the field, but merely that it was not clearly separated on the plate measured. Several of these photographs were made in the first order.

TABLE V—*Continued*

Wave-Length	Δλ, Spark	Δλ, Spark / 2.9	Width in Spots	δ
5404.36	0.38	0.13	0.16	+0.03
5405.99	0.23	0.08	0.15	+0.07
5411.12	0.40	0.14	0.13	−0.01
5415.42	0.38	0.13	0.15	+0.02
5424.29	0.40	0.14	0.15	+0.01
5429.92	0.48	0.16	0.16	0.00
5434.74	single		0.11	
5447.13	0.51	0.18	0.19	+0.01
5455.83	single		0.20	

the temperature is higher and the field weaker. In this case, the field intensities indicated by the enhanced lines should be below the average value. In view of the fact that the rate of change of intensity with level is not the same for all lines, it is evident that many more cases must be included in any satisfactory test of this hypothesis. From the same course of reasoning it follows that lines which are most strengthened in spots should, in general, be most widened. This appears to be true, but a careful quantitative comparison will be made, both for strengthened and weakened lines, and published in a subsequent paper. It must not be forgotten that a considerable increase of temperature in the higher spot vapors would tend to produce true reversals. Discussion of this question must be reserved, however, until the spot spectra can be more thoroughly studied with this point in view.

In Table IV the mean residual, taken without regard to sign, is 0.021 Ångströms. If we omit the enhanced lines, because of their exceptional behavior in spots, the mean residual is reduced to 0.015 Ångströms. As the spot lines range in width from 0.14 to 0.24 Ångströms, the agreement is closer than would be expected to result from chance alone. When it is remembered that one or more secondary causes may also affect the width of the lines, the probability that a true relationship exists appears to be considerably increased.

A more refrangible region of the iron spectrum gives the results detailed in Table V.

Here the mean residual is 0.021 and the range in the width of the spot lines from 0.09 to 0.20 Ångströms. λ 5107.82, λ 5123.90, λ 5198.89, and λ 5434.74, which are very narrow in spots, are not quite separated on the laboratory plates. λ 5455.83, on the contrary, is single in the laboratory and fairly wide in spots. In this case, at least, there must be some cause of widening in spots other than a magnetic field.

A still more refrangible region of the iron spectrum gives the results contained in the following table:

TABLE VI

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	Δλ, Spark	$\frac{\Delta\lambda, \text{Spark}}{2.1}$	Width in Spots	δ
4427.48	0.32	0.15	0.16	+0.01
4433.39	0.28	0.13	0.12	−0.01
4442.51	0.35	0.17	0.18	+0.01
4443.36	0.10	0.05	0.12	+0.07
4454.55	0.26	0.12	0.10	−0.02
4459.30	0.32	0.15	0.12	−0.03
4461.82	0.32	0.15	0.14	−0.01
4466.73	0.26	0.12	0.15	+0.03
4469.54	0.32	0.15	0.12	−0.03
4484.39	0.29	0.14	0.12	−0.02
4494.74	0.25	0.12	0.14	+0.02
4522.80	0.20	0.10	0.08	−0.02 Enhanced line
4525.31	0.32	0.15	0.11	−0.04
4528.80	0.27	0.13	0.13	0.00
4531.33	0.29	0.14	0.12	−0.02
4548.02	0.22	0.10	0.10	0.00
4549.64	0.24	0.11	0.10	−0.01 Enhanced line
4556.06	0.27	0.13	0.12	−0.01 Enhanced line
4603.13	0.37	0.18	0.14	−0.04
	Mean 0.27		Mean 0.12	

It is interesting to note the progressive decrease toward the violet in the mean width of spot lines and the separation of the corresponding doublets in the spark, as shown by the following table. The means represent the three groups of lines given in Tables IV, V, and VI.

TABLE VII

Mean Wave-Length	Spot Lines Mean Width	Spark Doublets Mean Separation
6330	0.18	0.54
5267	0.14	0.42
4495	0.13	0.29

Although the rate of decrease is more rapid for the spark doublets than for the spot lines, it must be remembered that in the former case the mean separation of the components is given, while the mean width of the spot lines represents the separation of the components plus their width. The width of the components cannot be determined, except in the case of doublets, and therefore the rate of decrease falls off toward the violet, as the width of the spot lines approaches that of the solar lines. The extremely small average shift of the lines in the violet when the Nicol is rotated is in harmony with this view.

A group of twelve spot doublets near λ 4395, which belong to several different elements and have not yet been photographed in our laboratory, afford some additional evidence. The mean separations of groups of spot doublets in the red (Tables I, *Fe*, and II, *Ti*), green (Table III, *Cr*), and violet (those just mentioned) are given in the following table:

TABLE VIII

Mean Wave-Length	Spot Doublets	
	Number	Mean Separation
6186	9	0.137
5665	8	0.145
4395	12	0.085

Between λ 6186 and λ 5665 these doublets show no such progressive change as appears in Table VII.

Preston's law, $\frac{\Delta\lambda}{\lambda^2}=\text{const.}$, has been found to hold rigorously only for the lines of certain series. It therefore could not be expected to apply with accuracy here, especially as the lines of different elements are included. Nevertheless it is of interest to determine whether the decrease in the separation of these doublets toward the violet proceeds at a similar rate. If we combine the separations for λ 6186 and λ 5665, we have 0.141 for the mean wave-length λ 5941. Then

$$\frac{0.141}{(5941)^2}=4.0\times 10^{-9}$$

$$\frac{0.085}{(4395)^2}=4.4\times 10^{-9}.$$

The iron doublets, whose mean separations for a field strength of about 15,000 gausses are given in Table VII, yield the following results.

$$\frac{0.44}{(5544)^2}=14.3\times10^{-9}$$

$$\frac{0.29}{(4495)^2}=14.3\times10^{-9}.$$

Thus the iron doublets follow the law very closely, while the approximate agreement with the spot doublets, though perhaps the result of chance, is not without interest.

Table IX gives the widths of various titanium lines in spots, and the separations of the components of the corresponding doublets, observed along the lines of force in a field of 12,500 gausses.

TABLE IX

WIDTHS OF TITANIUM LINES

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{3.4}$	Width in Spots	δ
5823.91	single		0.13	
5866.68	0.48	0.14	0.19	+0.05
5880.49	0.64	0.19	0.19	0.00
5899.52	0.50	0.15	0.18	+0.03
5903.56	0.73	0.21	0.19	−0.02
5918.77	0.73	0.21	0.20	−0.01
5922.33	single		0.12	
5938.04	0.74	0.22	0.17	−0.05
5953.39	0.52	0.15	0.13	−0.02
5966.06	0.47	0.14	0.16	+0.02
5978.77	0.38	0.11	0.14	+0.03
6064.85	0.88	0.26	0.27	+0.01
6085.47	0.81	0.24	0.20	−0.04
6091.40	0.65	0.19	0.15	−0.04
6092.74	0.55	0.16	0.16	0.00
6098.87	0.59	0.17	0.15	−0.02
6121.22	0.56	0.16	0.17	+0.01
6126.44	0.64	0.19	0.17	−0.02
6146.44	single		0.12	
6261.32	0.41	0.12	0.16	+0.04
6317.67	0.42	0.12	0.12	0.00
6336.33	0.56	0.16	0.15	−0.01
6366.56	0.55	0.16	0.18	+0.02

For titanium in this region the mean residual is 0.021 Ångströms for spot lines ranging in width from 0.12 to 0.27 Ångströms.

SIGN OF THE CHARGE THAT PRODUCES THE FIELD IN SUN-SPOTS

If the evidence presented in this paper renders probable the existence of a magnetic field in sun-spots, it is of interest to inquire concerning the sign of the charge which, according to our hypothesis, produces the field. In Lorentz's theory of the Zeeman effect in its simplest form, the motion of a single electron in a molecule of a luminous source is discussed.[1] This electron is supposed to be capable of displacement in all directions from its position of equilibrium, toward which it is drawn by an elastic force, which is proportional to the displacement but independent of its direction. Let e be the charge of the particle, m its mass, fr the elastic force caused by a displacement r, f being a positive constant. The frequency of the vibrations, whether they be linear, elliptical, or circular, will be

$$n_0 = \sqrt{\frac{f}{m}}.$$

We may now suppose the light-source to be placed in a homogeneous magnetic field of intensity H. A particle carrying a charge e, and moving with velocity v, will be subjected to a force perpendicular to the field and to the direction of motion of the particle, the magnitude of which may be represented by $ev\mathrm{H}\sin(v, \mathrm{H})$. It is evident that the electron may have three different motions, each with its own frequency. Linear vibrations parallel to the lines of force, having the frequency n_0, will not be affected by the magnetic field. Circular vibrations in a plane perpendicular to the lines of force will be affected differently, depending upon whether they are right-handed or left-handed. If r is the radius of a circular orbit and n the frequency, the velocity of the electron will be $v = nr$ and the centripetal force will have the value mn^2r. We may now consider the effect on the motion of the electron of the elastic force fr and of an electromagnetic force

$$ev\mathrm{H} = enr\mathrm{H}.$$

For a positive charge the latter force is directed toward the center if the motion is clockwise, as seen by an observer toward whom the lines of force are directed. We then have

$$mn^2r = fr + enr\mathrm{H}.$$

[1] The following outline of the theory is taken from Lorentz's "Theorie des phénomènes magnéto-optiques récemment découverts," *Rapports*, Congrès international de physique, 3, 1, 1900.

This frequency n differs very slightly from the frequency n_0; thus the last term of the equation must be much smaller than the term fr, so that we may write

$$n = n_0 + \frac{eH}{2m}. \qquad (1)$$

This expression gives the frequency of the right-handed (clockwise) vibrations. For the left-handed vibrations we have

$$n = n_0 - \frac{eH}{2m}. \qquad (2)$$

As seen along the lines of force a single line in the spectrum is thus transformed into a doublet, the components of which are circularly polarized. An observer toward whom the lines of force are directed will find that the light of the component of greater wave-length, whose frequency has been decreased by the field, is circularly polarized in the right-handed or clockwise direction. Hence (2) is greater than (1), and it follows that the charge e of the electron which produces the spectral lines must be negative.

In the case of the solar vortices we have to consider two sets of charged particles, which may be entirely distinct from one another: (1) those whose vibrations give rise to the lines in the spectra of spots, and (2) those that carry the charge which, by the hypothesis, produces the magnetic field. The Zeeman effect supplies the means of determining the direction of the lines of force of the sun-spot fields, and photographs of the vortices, made with the spectroheliograph, indicate the direction of their rotation. Thus we are in a position to determine the sign of the charge carried by the particles which produce the fields. As pointed out independently by König and Cornu, the violet component of a magnetic doublet observed along the lines of force is formed by circular vibrations, having the direction of the current flowing through the coils of the magnet.[1] From observations of circularly polarized light, made in our Mount Wilson laboratory by Dr. St. John and confirmed by myself, it appears that when the Nicol prism of the tower spectrograph stands at 60° E. it transmits the violet component of a doublet produced in a magnetic field directed toward the observer. From Biot and Savart's law the direction of

[1] See Cotton, *Le phénomène de Zeeman*, chap. vii; König, *Wied. Ann.*, **62**, 240, 1897.

the current causing such a field is counter-clockwise, as seen by the observer. In the same position the Nicol also transmits the violet component of a doublet produced in a sun-spot surrounded by a vortex rotating clockwise. As a negative charge rotating clockwise produces a field of the same polarity as an electric current flowing counter-clockwise, we may conclude that the magnetic field in spots is caused by the motion of negative ions or electrons.

PROBABLE SOURCE OF THE NEGATIVE CORPUSCLES

We may now consider the probable source of a sufficient number of negative corpuscles to produce a field of about 2900 gausses in sun-spots.

In his *Conduction of Electricity through Gases*, p. 164, J. J. Thomson writes as follows:

> We thus are led to the conclusion that from an incandescent metal or glowing piece of carbon "corpuscles" are projected, and though we have as yet no exact measurements for carbon, the rate of emission must, by comparison with the known much smaller rate for platinum, amount in the case of a carbon filament at its highest point of incandescence to a current equal to several amperes per square centimeter of surface. This fact may have an important application to some cosmical phenomena, since, according to the generally received opinion, the photosphere of the sun contains large quantities of glowing carbon; this carbon will emit corpuscles unless the sun by the loss of its corpuscles at an earlier stage has acquired such a large charge of positive electricity that the attraction of this is sufficient to prevent the negatively electrified particles from getting right away from the sun; yet even in this case, if the temperature were from any cause to rise above its average value, corpuscles would stream away from the sun into the surrounding space.

On another page (168) Thomson also remarks: "The emission of the negative corpuscles from heated substances is not, I think, confined to the solid state, but is a property of the atom in whatever state of physical aggregation it may occur, including the gaseous." After illustrating this in the case of sodium vapor, Thomson adds (p. 168):

> The emission of the negatively electrified corpuscles from sodium atoms is conspicuous as it occurs at an exceptionally low temperature; that this emission occurs in other cases although at very much higher temperatures is, I think, shown by the conductivity of very hot gases (or at any rate by that part of it which is not due to ionization occurring at the surface of glowing metals), and especially by the very high velocity possessed by the negative ions in the case

of these gases; the emission of negatively electrified corpuscles from atoms at a very high temperature is thus a property of a very large number of elements, possibly of all.

Thus the chromosphere, as well as the photosphere, may be regarded as copious sources of negatively electrified corpuscles. The part played by these corpuscles in the sun-spots cannot be advantageously discussed until the nature of the vortices is better understood.[1] At present it is enough to recognize that the supply of negative electricity appears amply sufficient to account for the magnetic fields.

Let n be the number of corpuscles per unit cross-section passing a given point in unit time and e the charge on each corpuscle. Then we have, for the current carried by the corpuscles, $c=ne$. H. A. Wilson found that in a vacuum tube, at pressures up to 8.5 mm, the current at the cathode was $0.4\,p$ milliamperes per sq. cm, where p is the pressure in millimeters.[2] If $p=8.5$, we have $c=3.4\times 10^{-3}$ amperes. Assume the velocity of the corpuscles in this case to be of the order of 10^4 km per sec. In a solar vortex (if the charged particles are carried with it) the velocity may be taken as of the order of 100 km per sec.[3] Then if the number of corpuscles per sq. cm were the same in the two cases, the current in the sun would be of the order of 3.4×10^{-5} amperes per sq. cm at the same pressure.

We m y now assume the corpuscles to be moving at a velocity of 100 km per second in an annulus 25,000 km wide, 1000 km deep, and 100,000 km in diameter surrounding a sun-spot. Taking the current strength to be as above, 3.4×10^{-5} amperes per sq. cm, the intensity of the resulting magnetic field comes out 1000 gausses.

Such a calculation is of little value, except for the purpose of indicating that a magnetic field of the observed order of magnitude might conceivably be produced on the sun.[4]

EXTERNAL FIELD OF SUN-SPOTS

We have already seen that the strength of the field in spots apparently changes very rapidly along a solar radius, and is small at the upper level of the chromosphere.

[1] For this reason a discussion of the very interesting suggestion of Professor E. F. Nichols, that the positively and negatively charged particles are separated by centrifugal action in the spot vortex, is reserved for a subsequent paper.

[2] *Philosophical Magazine* (6), **4**, 613, 1902. [3] *Solar Vortices*, p. 13.

[4] See a similar calculation by Zeeman in *Nature* for August 20, 1908.

If subsequent work proves this to be the case, it will appear very improbable (as indicated by theory) that terrestrial magnetic storms are caused by the direct effect of the magnetic fields in sun-spots. Their origin may be sought with more hope of success in the eruptions shown on spectroheliograph plates in the regions surrounding spots.

CONCLUSION

Although the combined evidence presented in this paper seems to indicate the probable existence of a magnetic field in sun-spots, the weak points of the argument should be clearly recognized. Among these are the following:

1. The failure of our photographs to show the central line of spot triplets before the spots are very close to the limb.

2. The presence in the spot spectrum of at least one triplet, which appears as a doublet when observed along the lines of force in the laboratory.

3. The absence of evidence to support the hypothesis that the imperfect agreement between spot and laboratory results is due to differences in the mean level of absorption.

4. The apparent constancy of the field strength, as indicated by the nearly uniform width of the doublets in different spots.

5. The difficulty of explaining, on the basis of our present fragmentary knowledge of solar vortices, the observed strength of field in the umbra and penumbra, and especially its variation with level.

As the resolving power of the 30-foot spectrograph is sufficient to resolve completely only the wider spot doublets, the central line could not be separately distinguished in other cases, even if it were present. Hitherto it has been possible to photograph the spectra of only the largest spots, because the images of other spots, as given by the tower telescope, are too small. The need of a telescope giving a much larger image of the sun, and a spectrograph of greater resolving power and focal length, which has been felt in previous work, is strongly emphasized by this investigation. Such apparatus would also permit the spectrum of the chromosphere, and many other solar phenomena, to be studied to great advantage.

As regards the nature of the vortices, the principal question is whether the gyratory motion primarily concerned in the production of the magnetic field is outside the boundaries of the spot or within the umbra. In the former case we must face various difficulties, such as the apparent constancy of the field in different spots, and the fact that its intensity rapidly decreases upward. If a spot vortex may be considcred analogous to an anti-cyclone, and the assumption be made that the gyratory motion of the low-level vapors produces the field, these difficulties may be lessened. The view that the field is produced by the gyratory motion of vapors within the umbra raises other difficulties which may also be serious. Fortunately there is reason to hope that observations now in progress may throw light on several of these questions.

Mount Wilson Solar Observatory
October 7, 1908

ADDENDUM

The fact that the doublets in the sun-spot spectrum do not change to triplets, even when the spot is as much as 60° from the center of the sun, appeared, when the proof of the above paper was corrected, to be a serious argument against the magnetic field hypothesis. Thanks to the recent work of Dr. King, this difficulty no longer exists, at least in the case of several iron and titanium lines. Photographs of the spark spectrum in a strong magnetic field, taken at right angles to the lines of force, show that the iron lines $\lambda\lambda$ 6213.14, 6301.72, and 6337.05 are doublets, with no trace of a central component. As these lines are also doublets when observed parallel to the lines of force, it is only natural that they should be double in spots, wherever situated on the solar disk. λ 6173.55, which is a fine triplet in spots, is a triplet when observed at right angles to the lines of force. But the line λ 6302.71 is the most interesting of all. In Table I this is classed as a spot doublet. In the spot spectrum the line appears as a triplet, but so decidedly asymmetrical that I supposed the intermediate line to be due to some element other than iron, greatly strengthened in the spot. It now turns out, however, that this is an asymmetrical triplet in the spark, when observed at right angles to the lines of force. Moreover, the displacement of the intermediate line from the center is toward the red, both in the spot and in the spark. As soon as a suitable photograph can be taken in a higher order of the grating, it will be possible to measure the asymmetry in the spark, as has already been done in the spot spectrum.

The titanium lines $\lambda\lambda$ 6303.98 and 6312.46, which are double in spots, are also double in the spark, when observed at right angles to the lines of force. λ 6064.85, already mentioned as a triplet in spots, with a rather faint central component, is a triplet, with strong central component, in the spark under the above conditions.

The titanium spot doublets $\lambda\lambda$ 5903.56 and 5938.04 (Table II) have not yet been observed at right angles to the lines of force.

These results leave no doubt in my mind that the doublets and triplets in the sun-spot spectrum are actually due to a magnetic field. As I am now designing a spectrograph of 75 feet (23 m) focal length, for use with a tower telescope of 150 feet (46 m) focal length, I hope it may become possible to investigate small spots, as well as large ones, and to resolve many of the close doublets and triplets in their spectra.

November 4, 1908