THE MAGNETIC POLARITY OF SUN-SPOTS[1]

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Whirling storms in the earth's atmosphere, whether cyclones or tornadoes, follow a well-known law which is said to have no exceptions: the direction of whirl in the Northern Hemisphere is left-handed or counterclockwise, while in the Southern Hemisphere it is right-handed or clockwise. The theory of terrestrial cyclones is still very obscure, but the direction of whirl is evidently determined by the increase in linear velocity of the air from pole to equator, due to the earth's rotation. The question naturally arises whether storms in the solar atmosphere are also whirlwinds, and, if so, what law governs their direction of whirl in the Northern and Southern hemispheres.

The first definite evidence bearing on this question was obtained with the spectroheliograph in 1908.[2] Photographs of the hydrogen flocculi made with the Hα line showed clearly marked vortical structure in regions centering in sun-spots. This structure was found to be repeated in hundreds of spots, leaving no doubt as to the generality of the phenomenon. Furthermore, photographs were obtained showing masses of hydrogen in the act of being drawn from a great distance toward the center of sun-spots, as though sucked into a vortex.

These photographs suggested the hypothesis that a sun-spot is a vortex, in which electrified particles, produced by ionization in the solar atmosphere, are whirled at high velocity. This might give rise to magnetic fields in sun-spots, regarded as electric vortices. A search for the Zeeman effect led to its immediate detection, and abundant proofs were soon found of the existence of a magnetic field in every sun-spot observed.[3]

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 165.

[2] Hale, "Solar Vortices," *Mt. Wilson Contr.*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[3] Hale, "On the Probable Existence of a Magnetic Field in Sun-Spots," *Mt. Wilson Contr.*, No. 30; *Astrophysical Journal*, **28**, 315, 1908.

Subsequent investigations have led to the view that two classes of vortices are involved:

1. High-level hydrogen vortices, centering in sun-spots, which are revealed by the spectroheliograph when monochromatic images of the sun are photographed with the light of the central part of the Hα line. In these vortices, which sometimes cover vast areas of the solar surface, the motion of the hydrogen appears to be spirally inward and downward. Little is known, except by inference, as to the form of the stream-lines in the lower levels close to the photosphere. There is reason to infer, however, that the hydrogen gas, descending toward the solar surface, moves spirally outward in the lower chromosphere above the spots.[1]

2. Low-level electric vortices, formed in the photosphere, which constitute the sun-spots themselves. In these vortices the motion of the gases appears to be spirally upward from within the photosphere and outward along its surface.[2] It is easy to show by laboratory experiments that such a primary vortex formed in water may set up a secondary vortex in a gaseous atmosphere above it, closely analogous to the hydrogen vortices above sun-spots.

The present paper deals with the magnetic polarity of sun-spots, though some reference will also be made to the closely related phenomena exhibited by the vortex structure of the hydrogen flocculi. The purpose in view is to discover the law of magnetic polarities, if such exists, and to consider whether this law is subject to variation in the course of the sun-spot cycle. Subsequent papers will deal with the various magnetic peculiarities of sun-spots and the structure of the hydrogen flocculi, with special reference to the nature of the vortices associated with sun-spots.

METHOD OF OBSERVATION

It is a well-known fact that when a normal Zeeman triplet is observed along the lines of force of a magnetic field the central (p) component is absent and the two side (n) components are circularly polarized in opposite directions. A quarter-wave plate and Nicol

[1] St. John, *Mt. Wilson Contr.*, No. 69; *Astrophysical Journal*, **37**, 322, 1913; Evershed, *Kodaikanal Observatory Bulletin*, No. 15; Memoirs, **1**, Pt. 1, 1909.

[2] St. John, *loc. cit.*

prism mounted over the slit of the spectroscope permit either *n*-component to be cut off at will by rotating the Nicol. Furthermore, if the polarizing apparatus be adjusted so as to extinguish one component, reversal of the current through the coils of the magnet will cause this component to reappear, while the other will be extinguished. The method thus offers a simple means of determining the polarity of a magnetic field, which can still be used when the angle between the line of sight and the lines of force is as great as sixty or seventy degrees. In this case, however, the *p*-component of the triplet is present, and the elliptically polarized light of the *n*-components can be only partially extinguished.

This method is employed daily for the study of the magnetic polarity of sun-spots with the aid of the 75-foot spectrograph of the 150-foot tower telescope on Mount Wilson. A 12-inch (30.5 cm) visual objective of 150 feet focal length, mounted just below the second mirror of the coelostat near the summit of the tower, produces at the base of the tower an image of the sun about 43 cm in diameter, any portion of which may be brought upon the slit of the spectrograph below by means of the electric motors that control the slow motions of the coelostat and second mirror. The massive circular head of the spectrograph, which carries the slit in a horizontal plane, can be rotated to any desired position angle. After passing through the slit, the light from the sun-spot, or other portion of the solar image, descends vertically into a subterranean well, 10 feet (3.0 m) in diameter, with concrete walls. The collimating lens of 6-inch (152 mm) aperture is 75 feet (22.9 m) below the slit. This lens and the large Michelson grating below it are mounted on a heavy support at the bottom of the well, where the temperature is essentially constant throughout the year. After falling on the grating, the light is returned through the collimating lens, which forms an image of the spectrum at a point near the slit of the spectrograph. Here it can be observed visually, or photographed if desired. There is no connection (other than the walls of the well) between the head of the spectrograph, which carries the slit, and the support for the collimator-camera lens and grating at the bottom of the well. When the slit is rotated in position angle, the grating support is rotated through the same angle by means of an electric motor, thus bringing the lines of the grating again into parallelism with the slit. All of the necessary adjustments, including the rotation of the dome at the summit of the tower, the slow motions of the coelostat and second mirror, the focusing of the sun's image on the slit, the focusing of the collimator-camera lens, the inclination of the grating to bring different orders of spectra into view, and the rotation in azimuth of the grating support, are accomplished by electric motors controlled by push buttons near the hand of the observer.

Most of the observations, both visual and photographic, of the Zeeman effect in sun-spots are made in the second-order spectrum, where the linear dispersion at the region in question is 1 A = 2.96 mm. For the daily determination of spot polarities the sharp iron triplet λ 6173.553 is usually employed.

In work of this nature, as already stated, it is necessary to use a Nicol prism, which is supported just over the slit of the spectrograph, and surmounted by a compound quarter-wave plate, so constructed that the principal sections of the successive mica strips (2 mm wide) are normal to one another. The Nicol prism, 130 mm in length, 18 mm high, and 10 mm wide (effective width 5 mm), was built by Werlein (from four sections each 32.5 mm long) for use with the 75-foot spectrograph (see Plate III*a*, *Contribution* No. 71). The compound quarter-wave plate, there shown swung to one side, can be turned into position above the Nicol. In view of the considerable focal length of the spectrograph, the distance of the quarter-wave plate from the slit (65 mm) is not sufficient to reduce materially the sharpness of the dividing lines between adjoining strips of spectra. For the study of plane polarization phenomena, a compound half-wave plate is substitued for the compound quarter-wave plate. Circular half-wave and quarter-wave plates, mounted so that they can be rotated in position angle, are also used for special purposes.

With this apparatus the magnetic polarities and the strength of the magnetic field in all sun-spots are recorded daily (see Fig. 1). A sheet of paper is placed in the focal plane of the telescope and all spots visible are traced in outline upon it. The polarity of each spot is then indicated by a "V" or an "R," according as the violet

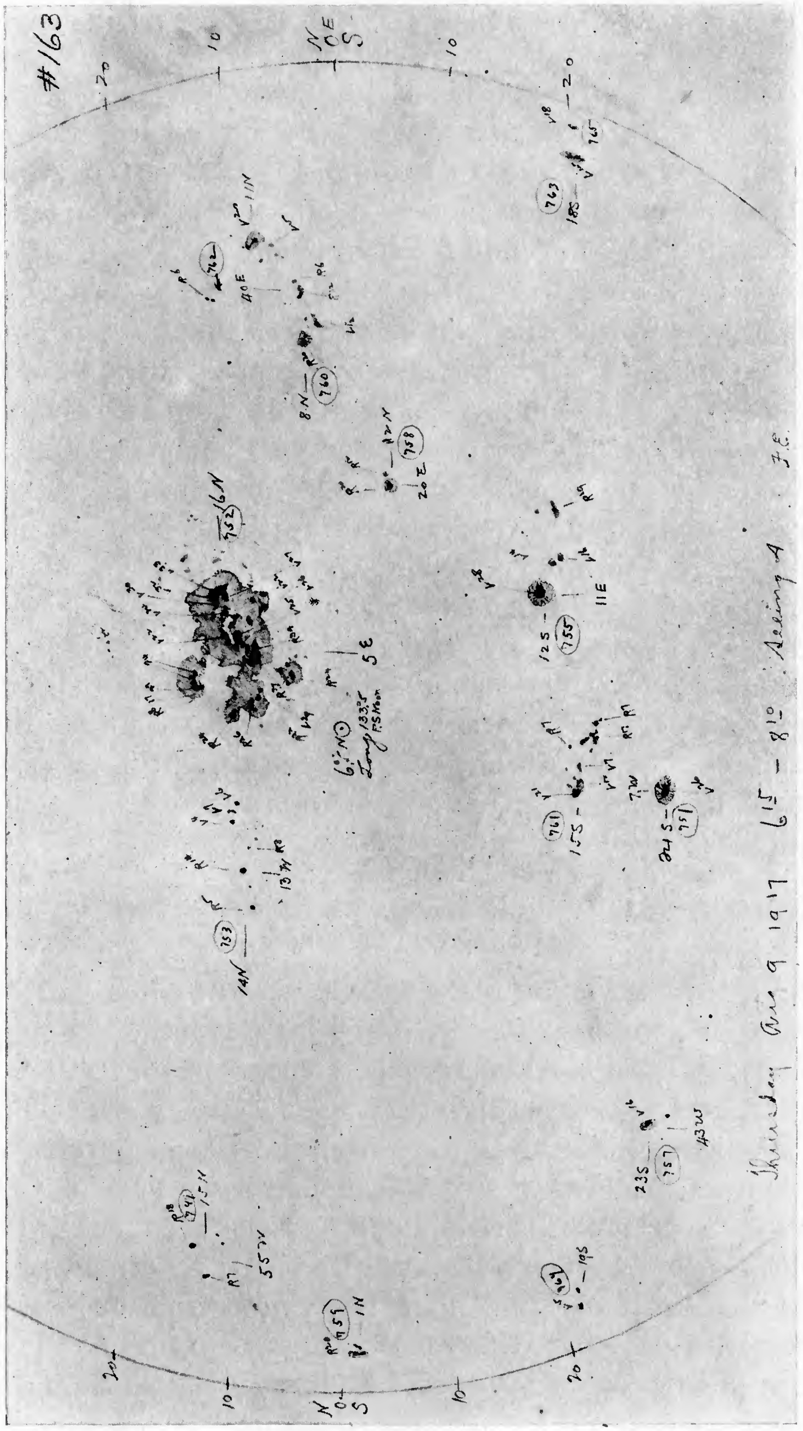


Fig. 1.—Reproduction of sketch showing daily record of observations of sun-spot polarities

or red component of the Zeeman triplet is transmitted by a given strip of the quarter-wave plate. As the diameter of the focal image of the sun is 43 cm, it is possible in this way to observe very small spots. In addition to the record of polarities, the strength of the field in each spot is measured by means of a parallel-plate micrometer. The scale of this micrometer has been carefully calibrated by Ellerman and Nicholson, and when used to measure a triplet whose separation for a given field-strength has been determined in the laboratory its readings are readily convertible into gausses. In the case of the sharp triplet λ 6173, the *n*-components may still be distinguished separately in sun-spots when the field-strength is as low as 1000 gausses. For greater field-strengths the observed values are therefore fairly reliable, but below this limit they must be regarded as merely approximate. The readings with the parallel-plate micrometer are recorded in degrees; and since for λ 6173 one degree corresponds approximately to 100 gausses, the designation "R 28" (see Fig. 2) at a certain point on a sun-spot indicates that the polarity at this point corresponds to that of the north magnetic pole of the earth, and that the field-strength is about 2800 gausses. "V 7" would mean that the polarity corresponds to that of the south magnetic pole of the earth, while the field-strength is of the order of 700 gausses.

THE DETERMINATION OF SUN-SPOT POLARITIES; INCLINATION OF THE LINES OF FORCE

The determination of the magnetic polarity of a sun-spot depends upon an estimate of the relative intensities of the red and violet components of a Zeeman triplet. The zinc triplet λ 4680 in the spectrum of a spark between the poles of a large Weiss magnet, when photographed with a Nicol prism and compound quarter-wave plate at angles of 0°, 60°, and 90° with the lines of force, presents the appearance shown in Plate V*a*, *b*, and *c*. When the observation is made parallel to the lines of force, the *p*-component of the triplet is absent and one of the *n*-components is completely cut off. At right angles to the lines of force the *p*-component is twice as strong as the *n*-components (in the case of a normal triplet), while the two *n*-components are of equal intensity. At intermediate angles the plane polarized p-component is of intermediate intensity, while the elliptically polarized n-components are no longer completely cut off by the Nicol prism and quarter-wave plate. The relative intensities of the three components of a normal triplet for

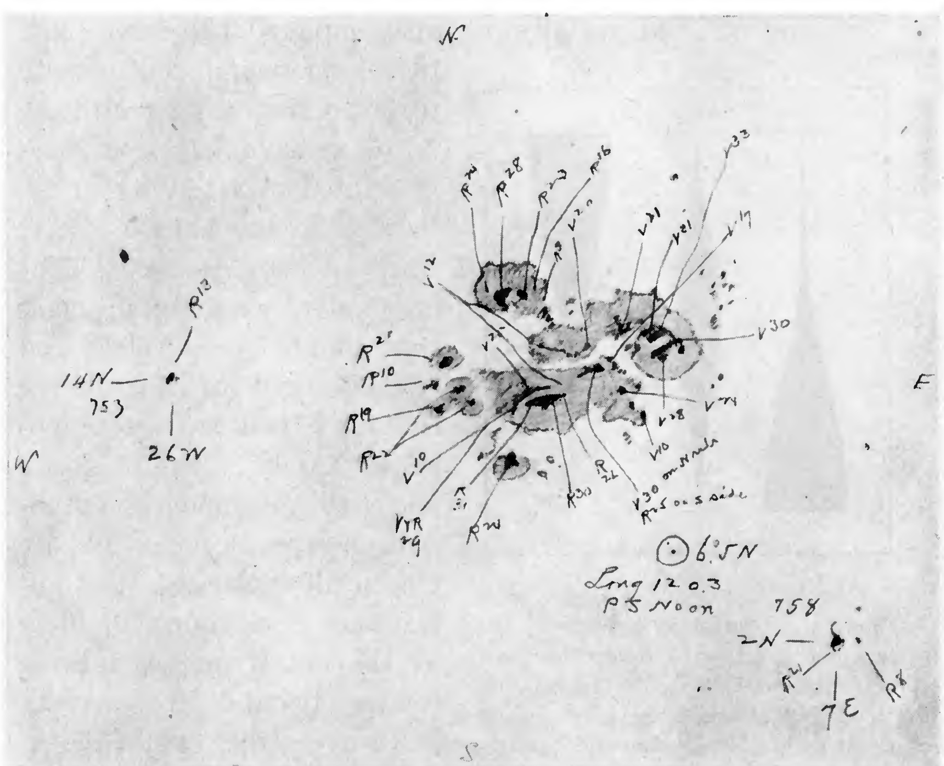


FIG. 2.—Sketch of large sun-spot group from the daily record for August 10, 1917, showing the manner of indicating the polarity and field-strength at different points in the group.

one set of alternate strips, when observed at any angle from 0° to 180° with the lines of force, are given by

$$n_V=\frac{1}{4}\,(1-\cos\gamma)^2 \quad p=\frac{1}{2}\sin^2\gamma \quad n_R=\frac{1}{4}\,(1+\cos\gamma)^2$$

where n_V, p, and n_R are the intensities of the violet, central, and red components respectively; γ is the angle between the line of sight and the lines of force, and the unit of intensity is such that $1=n_V+p+n_R$.[1] The variation of intensity in the three components with

[1] Seares, *Mt. Wilson Contr.*, No. 72, p. 5; *Astrophysical Journal*, **38**, 99, 1913.

the angle γ is illustrated by Fig. 3. We thus have a means of determining the angle between the line of sight and the lines of force in observations of sun-spots. The important bearing of this on polarity determinations will shortly appear.

Repeating the foregoing observations, at the same angles of 0°, 60°, and 90°, but substituting the compound half-wave plate for the compound quarter-wave plate previously used with the Nicol, we have the appearances illustrated in Plate V*d*, *e*, and *f*. Parallel to the lines of force, when no plane polarized light is present, we naturally find that the half-wave plate and Nicol are without effect on the circularly polarized *n*-components. At 60°, where the plane polarized *p*-component is absent and the *n*-components are elliptically polarized, the appearance is as shown in Plate V*e*, the central component being completely cut off by alternate half-wave strips, while the *n*-components are materially reduced in intensity.

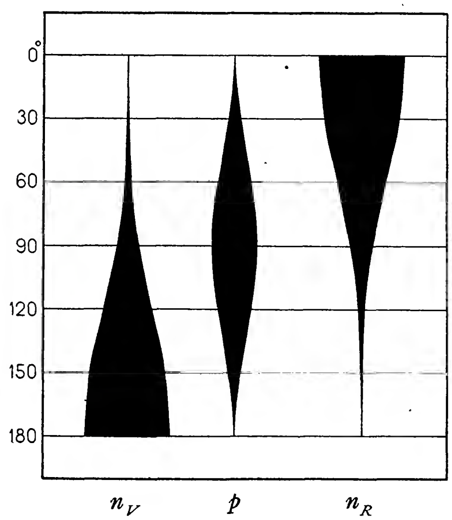


FIG. 3.—Relative intensities of the three components of a normal Zeeman triplet for inclinations of 0° to 180° between the line of sight and lines of force when observed with a Nicol prism and quarter-wave plate placed in front of the slit of the spectrograph. Thus for 0° the relative intensities are 0, 0, 1, respectively; for 90°: 0.25, 0.50, 0.25; for 180°: 1, 0, 0.

Consider now the bearing of these observations on the determination of the polarity of a sun-spot when close to the sun's limb. Let us assume that the lines of force at the center of the spot are parallel to a radius from the sun's center passing through this point, and that at other parts of the umbra and penumbra the lines of force are inclined approximately as indicated in Plate V*g*. This drawing relates to a spot photographed near the west limb of the sun on October 1, 1915, and reproduced in Plate *Vh*, where the scale is that of the image of the sun at the focus of the 150-foot tower telescope. The triplets λ 6302.709 and λ 6301.718 were observed at various parts of the spot, the successive positions of the slit on the image of the spot being indicated on the illustrations by the lines numbered 1 to 7. The observations were made visually by Hale in the second-order spectrum of the 75-foot spectrograph, using the Nicol and the compound quarter-wave plate over the slit. As these observations are typical of all fairly symmetrical spots when near the sun's limb, the phenomena observed at each position of the slit may be indicated here. Reference is made to the appearance of the triplet λ 6173.

1. Slight "zigzag" effect, red *n*-component (R) stronger than violet *n*-component (V). Diffuse.

2. Widened, diffuse. R stronger than V. Sharp at one point in spot, where *p* and R are separated. R stronger than *p*. V absent or very faint.

3. Wide, diffuse. R stronger than V. Three components of triplet sometimes visible.

Between (3) and (4). *p* visible but faint. V strong and separated from *p*. R apparently absent.

4. More diffuse. *p* hardly separated from V, which is very strong. Marked "zigzag."

5. Similar, but less "zigzag." Diffuse.

The chief point to be noticed is that, whereas the red *n*-component (R) was the stronger on the side of the spot toward the limb, the violet *n*-component (V) was the stronger on the opposite side of the spot. In other words, opposite polarities were indicated by the observations on the opposite sides of the spot. This is easily explained when the inclination of the lines of force at various points in the spot is considered.

As already stated, Plate V*h* represents the spot at the point of observation near the west limb of the sun. The direction of the lines of force corresponding to the various parts of the spot is hypothetically indicated in Plate V*g*. Thus when the slit occupied positions (2) and (3) the lines of force were directed away from the observer, and *R* was stronger than *V*.[1] Between (3) and (4) the *n*-components became of equal intensity, indicating that the line of sight was nearly at right angles to the lines of force. In subsequent positions of the slit the violet *n*-component, which had been

[1] Assuming the lines of force at the center of the spot to be directed radially outward from the sun's center.

weaker than the red component in positions (2) and (3), was invariably the stronger, showing that the lines of force from the inner side of the spot were directed toward the observer. Thus the true polarity of a sun-spot, corresponding with that given by observations made on the umbra when the spot is near the center of the sun, may also be determined near the limb by observing that portion of the penumbra which lies toward the center of the sun.

The observations indicate that at some position of the slit between (3) and (4) the lines of force were nearly at right angles to the line of sight. At this point the compound half-wave plate gave strong evidence of plane polarization (Plate V*k*), while the the quarter-wave plate indicated the same result by showing that maximum intensity shifted from *R* to *V*.

The position on the spot occupied by the slit when the red and violet components of a Zeeman triplet are of equal intensity may be called the "neutral line" (see Fig. 3). By determining the position of this line in a large number of spots we may obtain data which will enable us to fix, with some precision, the average inclination of the lines of force in a plane passing through the center of the sun and the line of sight.

The photographs of a large bipolar spot group made on February 9, 10, 12, 13, 14, 1917, and reproduced in Plate VI, will serve to illustrate how the position of the neutral line changes with the longitude. Observations were made on both of the principal spots as the group was carried by the solar rotation toward the west limb from a point near the center of the sun. One day's observations are missing, because of clouds. The gradual displacement with longitude of the neutral line illustrated by these observations is perfectly typical, and may be seen in any spot of sufficient size as it is carried by the solar rotation away from the eastern or toward the western limb.

Irregularities in the form of spots, the presence of small components opposite in polarity to the chief umbra, and other magnetic peculiarities such as are noted below, frequently complicate the observations and affect the form and position of the neutral line. But its average shift with longitude, determined from observations of a considerable number of spots, gives the approximate inclination of the lines of force in various parts of the umbra and penumbra. Thus we find, from 105 observations of 61 spots made by Joy and Nicholson, the positions of the neutral line and the corresponding inclination of the lines of force (taken as normal to the lines of sight passing through the neutral line) given in Table I.

The position of the neutral line is given in tenths of the spot's radius, measured from the center of the spot toward the limb. In the average spot of moderate size the radius of the umbra is 0.4 that of the penumbra.

TABLE I

INCLINATION OF LINES OF FORCE

Longitude	Position of Neutral Line	Angle Between Lines of Force and Solar Radius
30°–40°	8.0	55°
40 –50	7.0	45
50 –60	4.7	35
60 –70	3.2	25
70 –90	2.0	10

These results relate to the lines of force that lie in a plane passing through the center of the spot, the center of the sun, and the line of sight. They do not show, however, the inclination of the lines of force in the plane at right angles. These can be very accurately determined by a method first applied by Nicholson, as follows:

When light from a Zeeman triplet is examined in a direction normal to the lines of force the vibrations producing the *p*-component are parallel to the lines of force. When a sun-spot is observed near the sun's limb the lines of force lying in a meridional plane through the center of the spot are nearly normal to the line of sight, and their inclination to the north or south can be found by determining the direction in which the light of the *p*-component is vibrating. The simplest way to do this would be to pass the light through a Nicol and observe in what part of the spot the *p*-component is completely extinguished for a given position of the Nicol. For that region the lines of force would be parallel to the long diagonal. A modification of this method has been used because the grating over the 75-foot spectrograph almost completely plane-polarizes the light in the region generally observed, with the result that for certain positions of the Nicol it would be almost completely extinguished. The difficulty could be avoided by leaving the Nicol fixed with reference to the slit and rotating the whole spectrograph. In practice the same result is accomplished by using a half-wave plate placed over a fixed Nicol. The half-wave plate is mounted on a scale calibrated in degrees so that the angle between its principal axis and that of the Nicol can be observed. By observing this angle the direction of vibration of the *p*-component projected on a plane perpendicular to the line of sight can be determined in all parts of the spot. Since the plane through the sun's axis and the center of the spot is nearly perpendicular to the line of sight, observations of points in the spot lying in the plane give directly, with good approximation, the inclination of the lines of force toward the north or south. The results of 24 observations by Nicholson on three typical unipolar spots are as follows, the unit of distance, as before, being one-tenth of the radius of the spot.

Distance from Center of Spot	Angle Between Lines of Force and Solar Radius
0	0°
3	18
6	49
9	73

The inclinations found by the two methods are shown in Fig. 4, where the ordinates are angles between the lines of force and the solar radius and the abscissae are distances from the center of the spot. The results of the first method are indicated by crosses and of the second by circles. Considering the difficulties and uncertainties of observation, the agreement is excellent.

Additional information can be obtained by determining the relative intensities of the *n*- and *p*-components of a Zeeman triplet in different parts of a spot observed near the center of the sun. The results of such observations vary among themselves, but in many spots the *p*-component is strong even at the center of the umbra when the spot is near the center of the sun (see Plate V*i, j*). This investigation, the results of which are not essential in the present study of polarities, is being continued by Nicholson.

By taking into account the position of the neutral line and avoiding the observation of spots at the extreme limb of the sun (where the lines of force along the line of sight are frequently not visible at the outer edge of the spot), the polarities of sun-spots may be determined with certainty. It is to be understood that for this purpose a quarter-wave plate is always used with a Nicol prism over the slit of the spectroscope. Serious errors in the determination of the relative intensities of the lines of spot triplets

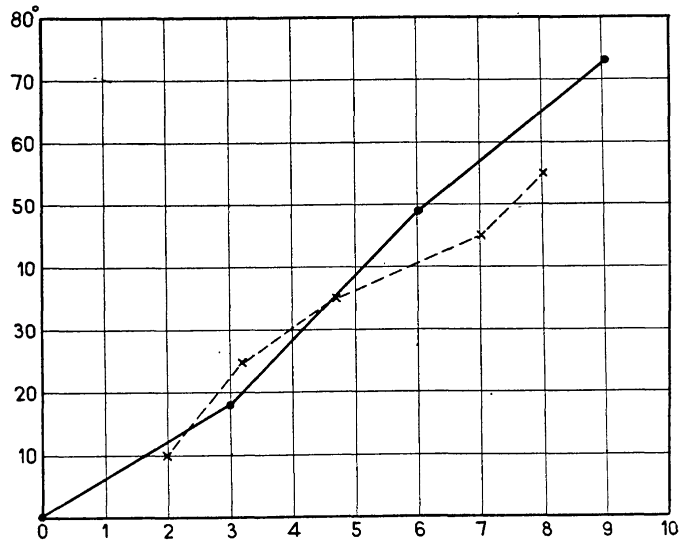


FIG. 4.—Inclination (ordinates) of lines of force to sun's radius at different distances from the center (abscissae, in tenths of radius of spot) of sun-spots. Crosses indicate results from observations of the position of the neutral line. Points are from measures of the orientation of the plane of polarization for the p-components in spots observed near the sun's limb.

may enter, as Zeeman has pointed out, when the observations are made without polarizing apparatus. In the case of the 75-foot spectrograph, for example, the plane polarization due to the grating varies greatly for different wave-lengths and for different orders of the spectrum. It is therefore entirely insufficient to determine the relative intensities of the lines without complete knowledge of the polarization phenomena of the grating and also those of the tower telescope. With a Nicol and quarter-wave plate, however, the results of polarity observations are essentially unaffected by these causes.

BIPOLAR SUN-SPOTS

In Hale's first paper "On the Probable Existence of a Magnetic Field in Sun-Spots,"[1] photographs were reproduced of two large spots, of opposite polarity, lying on opposite sides of the solar equator. Other cases which at first seemed to suggest a relationship between polarity and hemisphere were subsequently found. But it soon appeared that the simple law of terrestrial cyclones does not apply to the sun; for spots of opposite polarity were detected, not only in the same hemisphere, but also in the same spot-group.

Thus the large spot (Greenwich No. 6728) observed in the focal image of the 60-foot tower telescope on September 24, 1908, was seen to have at least three well-defined smaller umbrae, in addition to the principal umbra, within the boundary of the large penumbra. Photographs of the iron triplet λ 6303, made with the 30-foot spectrograph, showed the three small umbrae to have the same polarity, opposite to that of the principal umbra and penumbra. Many similar cases have been found, while cases of small companion spots, completely separated from a larger member of the group, and differing from it in polarity, are also common.

In one very remarkable instance, illustrated in Plate VII*a* and *b*, two large umbrae of the same spot, separated only by a bridge, were of opposite polarity, while the polarities of other members of the same group were as indicated in the sketch, Plate VII*c*, accompanying the photograph.

It fortunately happens, however, that cases of mixed polarity are not so common as to obscure our perception of a simple unifying principle leading directly to the detection of a general law of polarities. This has its origin in a well-known peculiarity of sun-spots, indicated in the records of the earliest observers, and commented upon by Carrington.

Sun-spots frequently occur in pairs, the principal members of which may be several degrees apart. The western or preceding member of such a group is often the first to be formed, but sooner or later a second spot, comparable with the first in size, but frequently smaller, or split into several components, is likely to appear behind it. Sometimes both members of the group appear simul-

[1] *Mt. Wilson Contr.*, No. 30; *Astrophysical Journal*, **28**, 315, 1908.

taneously, and in other cases the following member is formed first. Many minor spots usually accompany the larger ones, either clustered about them or lying in the space between the principal spots. It is probably a significant fact that the axis of the group usually makes only a small angle with the equator.

TABLE II

INCLINATION OF AXIS OF SUN-SPOT GROUPS

Semicycle	Latitude						
	0°–4°	5°–9°	10°–14°	15°–19°	20°–24°	25°–29°	30°–34°
Min.–Max. 1856–1860	7°(3)*	5°(27)	10°(69)	7°(94)	9°(103)	8°(60)	13°(20)
Max.–Min. 1860–1867	1 (24)	3 (117)	4 (148)	6 (73)	9 (40)	8 (9)	14 (3)
Min.–Max. 1867–1871	4 (4)	5 (15)	5 (55)	6 (80)	6 (97)	9 (45)	8 (23)
Max.–Min. 1871–1879	7 (35)	3 (139)	6 (147)	6 (90)	8 (65)	10 (13)	10 (13)
Min.–Max. 1879–1884	7 (11)	2 (42)	4 (105)	3 (123)	9 (85)	9 (31)	14 (9)
Max.–Min. 1885–1889	3 (34)	−1 (72)	6 (110)	7 (43)	10 (7)	17 (2)	(0)
Min.–Max. 1889–1893	−2 (7)	0 (21)	6 (81)	6 (93)	10 (88)	10 (46)	10 (12)
Weighted mean inclination and number of spots	3.7 (118)	2.4 (433)	5.6 (715)	5.8 (596)	8.7 (485)	9.3 (206)	10.8 (80)

* Quantities in parenthesis are numbers of spots.

A study by Joy of the sun-spot drawings of Carrington (1856–1861)[1] and Spörer (1861–1893)[2] shows that there is little change in this angle during the life of the group, but that in the mean the angle bears a definite relation to the latitude of the group. Twenty-six hundred and thirty-three bipolar and multiple groups, covering three and one-half sun-spot cycles, were examined. The following spot of the pair tends to appear farther from the equator than the preceding spot, and the higher the latitude, the greater is the inclination of the axis to the equator. This relation holds for both hemispheres. The details are shown in Table II and the results are illustrated in Fig. 5.

[1] *Observations of Spots on the Sun*, London, 1863.

[2] *Publicationender Astronomischen Gesellschaft*, **13**; *Pub. Astrophys. Obs. zu Potsdam*, No. 1, 1878; No. 5, 1880; No. 17, 1886; No. 32, 1894.

In general, the angle of inclination was found to depend entirely on the latitude of the group, without reference to the number of the cycle or the time within the cycle. A knowledge of the polarities of the spots would have aided greatly in determining the position of the axes of the groups.

The most significant characteristic of these binary spot-groups lies in the fact that the two principal members, whether single or multiple, are almost invariably of opposite magnetic polarity. A photograph made in the second-order spectrum of the 75-foot spectrograph will serve to illustrate this point, and at the same time to indicate how these polarity phenomena may be recorded photographically. The long Nicol prism and compound quarter-wave plate are used over the slit and the spectrograph is rotated in position angle until the slit passes through the two principal members of the group. A single exposure on a wide Zeeman triplet such as λ 6173 or λ 6303 then gives the polarity of the two members, as shown in Plate VII. The spot-group reproduced in Plate VII*d* from a direct photograph made with the Snow telescope on June 19, 1914, consisted of a larger preceding spot and two smaller spots to the east of it, with various minor companions between them. Plate VII*e*, from a photograph of the spectrum made with the long Nicol and single quarter-wave plate, shows that the two smaller spots were of the same polarity, but opposite to that of the largest spot. Plate VII*f*, taken with the compound quarter-wave plate, not only

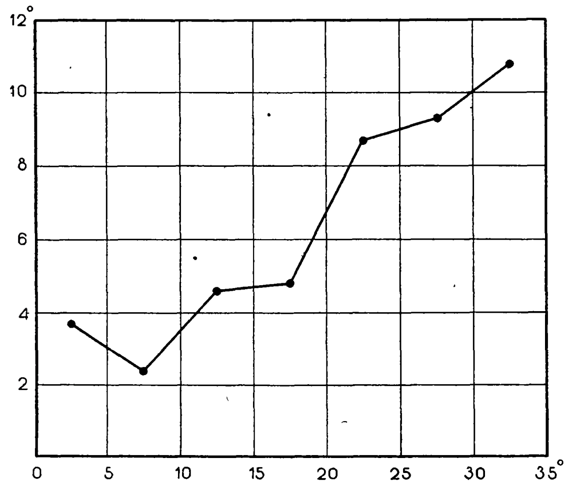


FIG. 5.—Summary of a statistical study of the sun-spot drawings of Carrington and Spörer showing the variation with latitude (abscissae) in the preferential inclination (ordinates) of the axis of bipolar sun-spot groups. In low latitudes the axes are nearly parallel to the sun's equator, but with increasing latitude the mean inclination increases to a maximum of about 11°.

confirms this result, but also serves to better advantage for the study of the weaker fields of the small companion spots lying between the preceding and following members of the group. It will be seen from this figure that magnetic displacements occur at points where no spots are shown, though faint indications of them appear in the original negative.

Analyzing these spectra, we find that there are apparently two "spheres of influence" of opposite polarity which meet near the center of the group. The first of these is dominated by the large preceding spot, while the other comprises the oppositely directed magnetic fields of the two following spots. Minor spots of opposite polarity sometimes occur, as already stated, within these "spheres of influence," but the generality of the bipolar effect is very strikingly shown by an examination of hundreds of spot-groups.

The preceding and following members of bipolar groups may be split into several components, often well separated, and small companion spots, of either polarity, may be present. Furthermore, the strength of the field and the area over which it can be detected may be very different for the preceding and following members of the group. But if magnetic fields of opposite polarity are distinctly shown by the preceding and following members of the pair, the essential characteristics of a bipolar group are present.

The tendency toward bipolar structure is so strongly marked that hardly more than 10 per cent of all spots observed are wholly free from it. In the case of spots which are apparently single, some traces of asymmetry, more or less suggestive of the structure of bipolar groups, can usually be detected. Sometimes such evidence of asymmetry is afforded by faculae following or preceding the spot. More commonly, however, especially in the central part of the sun, it is necessary to have recourse to spectroheliographic plates for the purpose of detecting the asymmetrical structure. In such photographs it is usually found that a single spot, or a group of small spots all having the same magnetic polarity, is near the preceding end of a mass of calcium flocculi elongated in a direction not greatly inclined to the solar equator. Much less frequently the spot occurs near the following end of such a group of flocculi. In about 10 per cent of all cases hitherto observed here the distribution of the flocculi is fairly symmetrical to the east and west of single spots.

Thus in the magnetic classification of sun-spots it is highly desirable to investigate the magnetic records in the light of information afforded by the distribution of the flocculi. The calcium flocculi serve admirably for the purpose just stated, but in order to study the characteristic vortex structure associated with bipolar spot groups we must have recourse to spectroheliograms of the hydrogen flocculi, taken under high dispersion with the light from the center of the Hα line.

In a later paper the characteristics of these bipolar groups will be discussed more in detail, and a variety of evidence bearing on their nature will be presented. Our immediate purpose is to present a scheme of magnetic classification and to bring out the fact that the recognition of this typical structure, even in the rudimentary form where the second spot is absent[1] and represented only by a train of flocculi, is essential to an intelligent discussion of the distribution of spots of different polarities in the northern and southern hemispheres of the sun.

The methods described above for recording polarities can of course be applied to the more complicated groups as well as to those of the simple bipolar type. A case of unusual complexity is illustrated and described in Plate VIII.

MAGNETIC CLASSIFICATION OF SUN-SPOTS

Our scheme of classifying sun-spots is based primarily upon the determination of their magnetic polarities. Supplementary evidence is frequently needed, however, and this is supplied, as already stated, by calcium and hydrogen spectroheliograms. Three classes of spots are included in the scheme: (α) unipolar, (β) bipolar, and (γ) multipolar. These may be subdivided as indicated below.

(α) *Unipolar spots*.—Single spots, or groups of small spots, having the same magnetic polarity. It should be noted, however, that

[1] In view of the fact that the general absorption in the spectrum of a spot increases greatly in passing from red to violet, it may perhaps become possible to photograph very faint spots, invisible to the eye, by using ultra-violet light of the shortest possible wave-length.

unipolar spots, and the chief components of bipolar groups, may occasionally have small companions of opposite polarity, which play such a minor and sporadic part in the group that they are disregarded in the classification.

Unipolar spots, whether single or multiple, may be divided into three groups, which are illustrated in Plate IX:

(*a*) Those in which the distribution of the calcium flocculi is fairly symmetrical preceding and following the center of the group.

(*ap*) Those in which the center of the spot-group precedes the center of the surrounding calcium flocculi.

(*af*) Those in which the center of the spot-group follows the center of the surrounding calcium flocculi.

(β) *Bipolar spots.*—The simplest and most characteristic bipolar spot-group consists of two spots of opposite polarity. The line joining the two spots generally makes only a small angle with the solar equator. Each member of the group may be accompanied or replaced by many small spots, but the great majority of the spots constituting the preceding and following members of the group are of opposite magnetic polarity. One or more companion spots, of polarity opposite to that which characterizes the corresponding region of the group, sometimes occur in association with either the preceding or following member.

Bipolar spots may be divided into four groups, illustrated in Plates X and XI$\beta\gamma$:

(β) Those in which the leading and following members, whether single or multiple, are approximately equal in area.

(βp) Those in which the leading member is the principal member of the group.

(βf) Those in which the following member is the principal member of the group.

($\beta\gamma$) Those in which the preceding or following members are accompanied by minor companions of opposite polarity.

(γ) *Multipolar spots.* Groups of this character, comprising hardly more than 1 per cent of the total number of spots observed, contain spots of both polarities so irregularly distributed as to prevent classification as bipolar groups (see Plates VIII*c* and XIγ).

MAGNETIC CLASSIFICATION OF 970 SUN-SPOTS OBSERVED DURING 1915–1917

While it is obvious that the changes that occur during the life of a spot must preclude a hard-and-fast determination of type, it may be interesting to give the preliminary results of a classification by Nicholson of the spots observed since our present method of recording was put into effect in 1915. In presenting the following figures it should be stated that they are provisional, and therefore subject to revision in the light of further study. Table III is self-explanatory, giving the number of spots observed in both hemispheres during 1915, 1916, and 1917, classified according to the system already explained.

Several interesting facts are brought out by this table. Most notable of these is the strong tendency toward the bipolar type, indicated not only by the large percentage of bipolar groups, but also by the small proportion of symmetrical unipolar spots. Another striking fact is the dominance of preceding spots, shown by the high percentage of βp spots as contrasted with βf spots, and also indicated by a similar preponderance of αp over αf spots. The constancy of the percentages for the successive years, and the very small number of multipolar (γ) spots, should also be noted.

The results of magnetic observation, revealing the great preponderance of bipolar groups, are closely in harmony with the conclusion reached by Father Cortie in his valuable paper "On the Types of Sun-Spot Disturbances."[1] After describing the various types, he remarks:

> The chief type, however, of which the above mentioned are in most, possibly in all, cases but phases, is the double-spot formation, with a train of smaller spots between the two principal spots of the group, the whole group generally drifting into more or less parallelism with the solar equator. In this form the principal spot, which eventually becomes a normal spot of regular outline, is generally the leading spot, but in many cases it is the following spot, while sometimes the preponderance in area alternates between the two, as the group traverses the disk. In yet rarer instances both the chief spots develop as regular spots.

A discussion of the details of sun-spot formation and dissolution, and of the relationship between spot polarities and the structure

[1] *Astrophysical Journal*, 13, 260, 1901.

of the accompanying hydrogen flocculi, must be reserved for another paper. Here it is our purpose to consider only such phases of these and other questions as bear directly upon the derivation of a law of sun-spot polarities.

TABLE III

MAGNETIC CLASSIFICATION OF 970 SPOTS

		α	αp	αf	β	βp	βf	$\beta\gamma$	γ	Unclassified	Total
1915	N	10	17	5	17	29	3	4	3	11	99
	S	7	16	4	21	22	6	4	0	3	83
	Total	17	33	9	38	51	9	8	3	14	182
	Percentages	9	18	5	21	28	5	4	2	8	
Total percentages		32			58						
1916	N	22	26	4	49	63	12	7	0	8	191
	S	31	28	8	17	37	13	6	0	7	147
	Total	53	54	12	66	100	25	13	0	15	338
	Percentages	16	16	4	20	30	7	4	0	4	
Total percentages		35			61						
1917	N	25	54	2	66	62	17	9	3	3	241
	S	16	41	7	53	69	11	7	0	5	209
	Total	41	95	9	119	131	28	16	3	8	450
	Percentages	9	21	2	26	29	6	4	1	2	
Total percentages		32			65						

SUMMARY (PERCENTAGES)

	α	αp	αf	β	βp	βf	$\beta\gamma$	γ	Unclassified
1915	9	18	5	21	28	5	4	2	8
1916	16	16	4	20	30	7	4	0	4
1917	9	21	2	26	29	6	4	1	2
Mean	11	18	4	22	29	6	4	1	5
Total number of spots	111	182	30	223	282	62	37	6	37

POLARITIES OF SPOTS IN THE NORTHERN AND SOUTHERN HEMISPHERES

For the purpose of deriving a law of sun-spot polarities we may regard unipolar spots (αp) followed by a train of flocculi as preceding spots of incomplete bipolar groups, and those (αf) which are preceded by a train of flocculi as following spots of such groups. During the last sun-spot cycle (observations from June 1908 to December 1912) it was found in the great majority of spots observed that the "marked strip" of the compound quarter-wave plate transmitted the violet component of preceding spots in the Northern Hemisphere and of following spots in the Southern Hemisphere.[1] It naturally follows, from the characteristics of bipolar groups, that during the same period the marked strip transmitted the red component of following spots in the Northern Hemisphere and of preceding spots in the Southern Hemisphere. The numbers of spots observed are given in Table IV.

TABLE IV

	Regular			Irregular			Range in Latitude	Average Latitude
	N V_p–R_f	S R_p–V_f	Total	N	S	Total		
Last cycle (June 1908 to December 1912)	7	17	24	0	2	2	18° to 3°	9°

Thus while the bipolar characteristic of sun-spots introduces an element not encountered in the case of terrestrial storms, the opposition in polarity north and south of the solar equator is analogous to the opposite direction of whirl, invariably observed in the case of northern and southern cyclones and tornadoes.

After the sun-spot minimum, which occurred in December 1912, we found, to our surprise, that the polarity of the members of bipolar groups was opposite to that observed before the minimum. That is to say, the marked strip of the compound quarter-wave plate now transmits the red component of the preceding spots of bipolar groups in the Northern Hemisphere and the violet component of the preceding spots of bipolar groups in the Southern Hemisphere.

This sudden change was so remarkable that it was feared some observational error had been made. The results have been checked

[1] Few spots were observed during this cycle, because attention was then concentrated upon a small number of very large spots.

repeatedly by different observers, however, and in all cases the conclusion has been the same. The first observations of the former cycle were made with the 60-foot tower telescope and 30-foot spectrograph, but before the end of the cycle the 150-foot tower telescope and 75-foot spectrograph were put into commission, and this work was transferred from the old to the new tower. Thus the danger of any confusion due to the change of spectrographs and polarizing apparatus was eliminated, as the results obtained with the 150-foot tower telescope during the former cycle were in harmony with those secured with the 60-foot tower telescope during the same period. During the former cycle the observations were both visual and photographic, but since the beginning of the present cycle most of the polarities have been determined visually, though the results have frequently been checked photographically.

TABLE V

Present Cycle	Regular			Irregular			Range in Latitude	Average Latitude
	N R_p-V_f	S V_p-R_f	Total	N	S	Total		
1913, 1914.....	18	14	32	1	1	2	34° to 13°	22°
1915..........	73	68	141	2	0	2	29 " 2	19
1916..........	166	120	286	7	7	14	37 " 4	17
1917..........	221	193	414	8	6	14	30 " 1	14

The observations of the present cycle are given in Table V, which corresponds with Table IV except for the fact that in Table V the polarities are classed as "regular" when the marked strip transmits the red component in preceding spots of the Northern Hemisphere, whereas during the former cycle it transmitted the violet component in such spots.

In a preliminary paper describing the observed change of polarity at the last sun-spot minimum,[1] it was suggested that the explanation might be connected with the difference in latitude of the spots of the old and new cycles. The mean latitude of the spots observed during the old cycle was 9°, while that of the spots

[1] Hale, *Mount Wilson Communication*, No. 10; *Proceedings National Academy of Sciences*, 1, 385, 1915.

observed up to that date during the new cycle was 23°. It therefore seemed possible that there might be two zones on the sun, of low and high latitude, in which the polarities of spots were of opposite sign.

This view of the case, however, has not been borne out by time, as the results given in Table V indicate. The percentage of irregular spots has not increased materially during the present cycle, although their mean latitude has decreased from 22° in 1913–1914 to 14° in 1917. The maximum of solar activity has also definitely passed, so that it can hardly be supposed that any reversal of polarity will be observed before the close of the cycle, unless it should be found to lag considerably behind the maximum.

DISCUSSION OF RESULTS

The present investigation should ultimately lead to the formulation of a definite law of sun-spot polarities, from which the polarities of normal spots of any type can be predicted for either hemisphere and for any epoch in the sun-spot cycle. We already know that the preceding and following spots of binary groups, with few exceptions, are of opposite polarity, and that the corresponding spots of such groups in the Northern and Southern hemispheres are also opposite in sign. Furthermore, the spots of the present cycle are opposite in polarity to those of the last cycle (see Fig. 6, in which these results are expressed graphically). It is evident, however, that the formulation of a law of polarities cannot be undertaken until after the close of the present cycle, when it will be learned whether a reversal of sign is actually characteristic of the sun-spot minimum.

After an empirical law of spot polarities has been formulated, the problem of its interpretation will remain. The possibility of expressing such a law in the same terms that apply in the case of terrestrial storms depends upon the possession of data still beyond our reach. Thus the view that sun-spots are vortices depends upon the assumption that the magnetic field must be caused by electrically charged particles whirling in a vortex. Supposing that the existence of a true hydrodynamical vortex and the direction of the whirl within it can be determined by observations of the Evershed effect, or in some other way, the sign of the dominant charge will follow at once from our knowledge of the magnetic polarity of the spot in question. Or, if the sign of the charge can be independently found, the direction of the whirl will follow.

In Hale's first paper on the Zeeman effect in sun-spots, the sign of the dominant charge was found to be negative by proceeding on the assumption that the direction of whirl in the spot vortex coincides with that in the hydrogen vortex above it. A long series of observations of the hydrogen flocculi has since shown that this assumption is probably unwarranted. A good majority of the hydrogen whirls associated with preceding spots are right-handed in the Southern Hemisphere and left-handed in the Northern Hemisphere, as in the case of terrestrial storms, but there are many exceptions to this rule. Moreover, the hydrogen whirls showed no reversal of direction at the sun-spot minimum, and during the present cycle we have found cases in which either right-handed or left-handed hydrogen whirls are associated with spots of a given polarity. The whole subject is so complex that it will be advantageous to postpone further discussion until the great mass of observational material at our disposal can be more exhaustively studied.

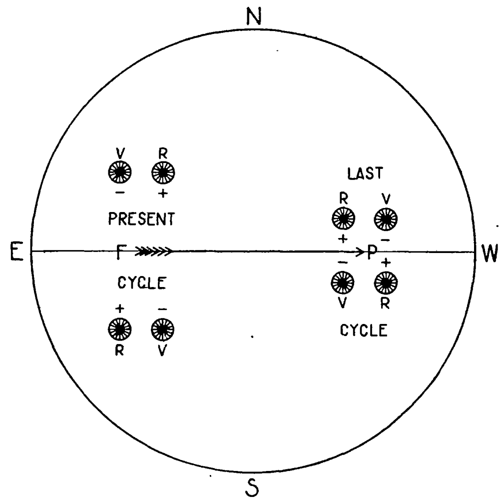


FIG. 6.—Diagram summarizing the results of polarity observations of sun-spots during the present and last cycles. The arrow indicates the direction of the sun's rotation; the letters *R* and *V*, the components of a normal triplet transmitted by the "marked strip" of the compound quarter-wave plate; and the algebraic signs, the distribution of the polarities between the preceding and following members of a bipolar group. Unipolar spots are normally of the same polarity as the preceding members of bipolar groups in the same hemisphere.

SUMMARY

1. The magnetic polarity of a sun-spot can be determined by observations, made with Nicol and quarter-wave plate, of the relative intensities of the *n*-components of a Zeeman triplet in its spectrum.

2. Such determinations of polarity can be made at almost any position on the sun's disk, but certain precautions must be taken to avoid error in the case of spots near the limb.

3. The inclination of the lines of force in sun-spots can be measured with considerable precision.

4. About 60 per cent of all sun-spots are binary groups, the single or multiple members of which are of opposite magnetic polarity.

5. Unipolar spots usually exhibit some of the characteristics of bipolar groups.

6. Before the last sun-spot minimum, the magnetic polarity of unipolar spots and of the preceding members of bipolar spots was positive in the southern and negative in the northern hemispheres of the sun.

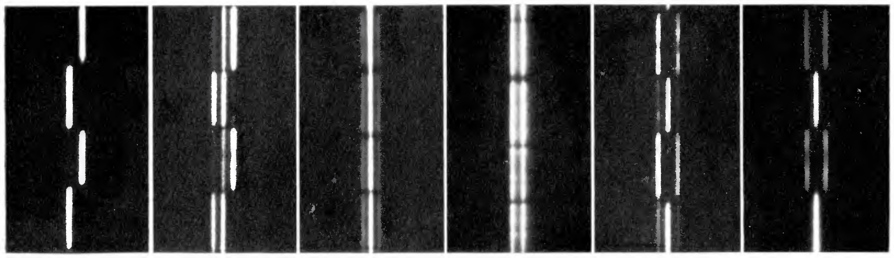
7. Since the minimum these signs have been reversed.

8. The paper describes a scheme of classifying sun-spots on the basis of their magnetic properties.

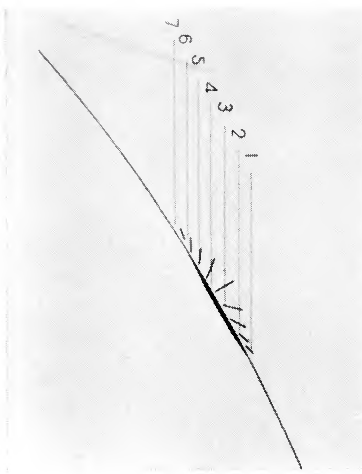
9. The results of a magnetic classification of 970 spots observed during the years 1915–1917 are briefly summarized.

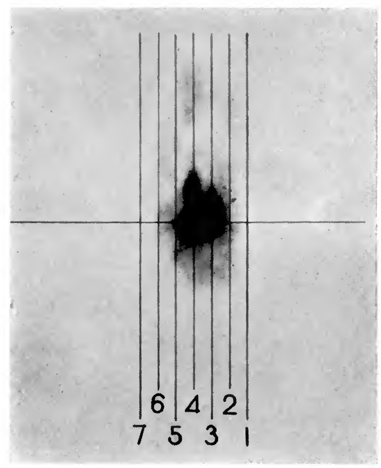
MOUNT WILSON SOLAR OBSERVATORY
November 11, 1918

PLATE V

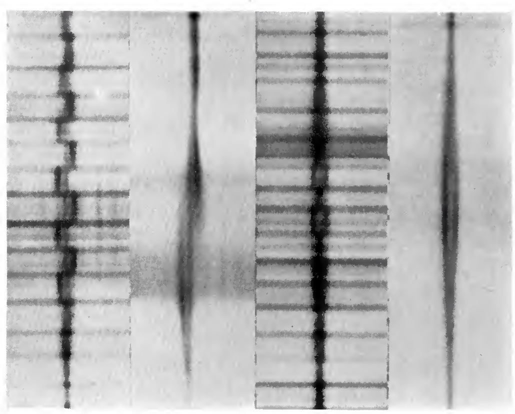


a *b* *c* *d* *e* *f*





g *h*



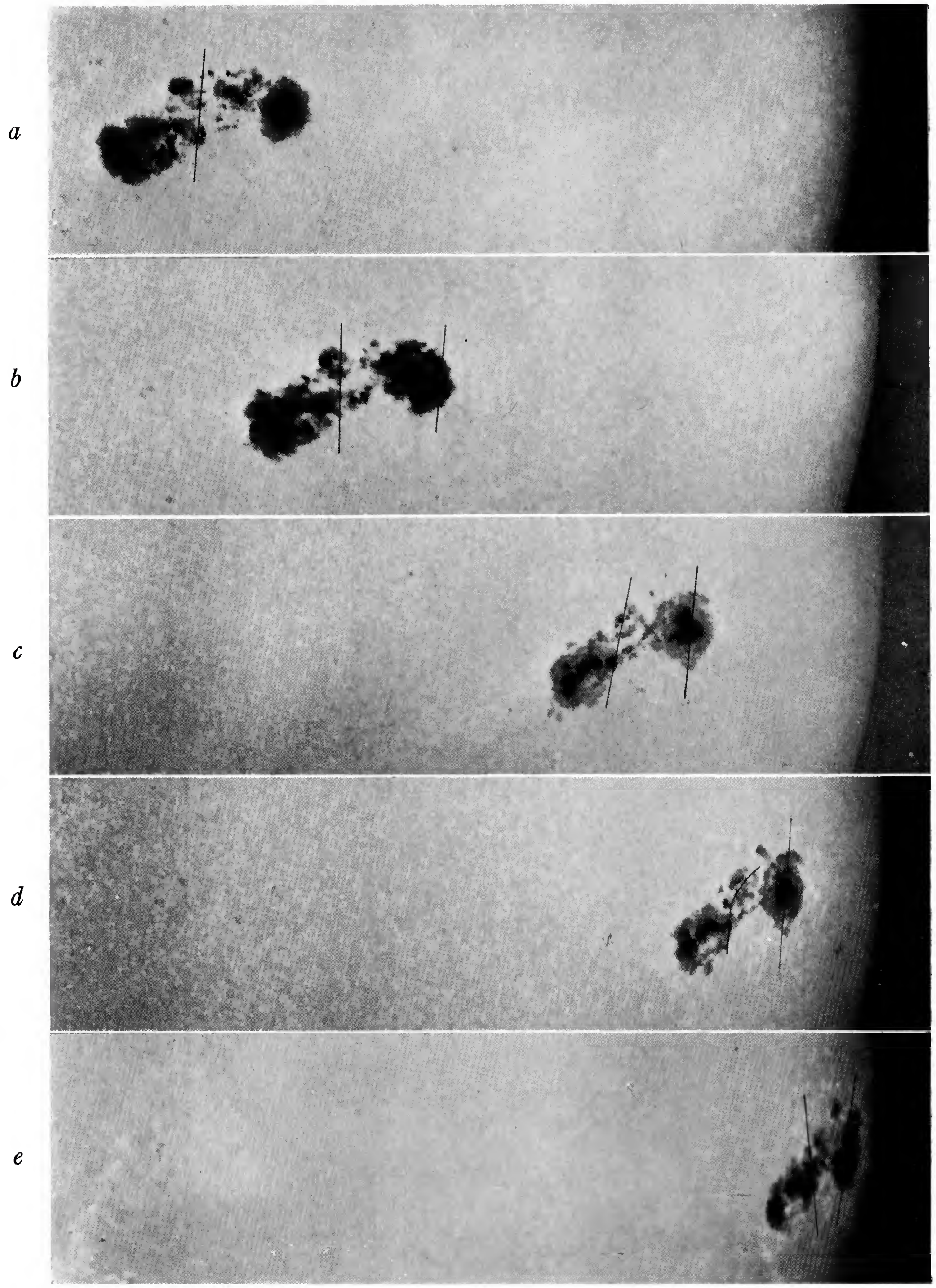
i *j* *k* *l*

a, *b*, *c*, Observations of the zinc triplet λ4680 in the physical laboratory, with compound quarter-wave plate in front of the slit of the spectrograph; inclinations of line of sight to lines of force are 0°, 60°, 90°, respectively; *d*, *e*, *f*, the same, with compound half-wave plate substituted for the quarter-wave plate; compare with Fig. 3 and *i* and *k* of this plate.

g, Lines of force in a sun-spot near the west limb on October 1, 1915; *h*, photograph of the same spot; the numbered lines indicate successive positions of the slit of the spectrograph used to determine the inclination of the lines of force.

i, *j*, *k*, *l*, Iron triplet λ 6173 photographed in spectra of various sun-spots; *i*, *j*, circularly polarized light, spot near center of sun, observed with Nicol and (*i*, compound; *j*, single) quarter-wave plate; *k*, *l*, plane polarized light, spot near limb, with Nicol and (*k*, compound; *l*, single) half-wave plate; *j* shows reversal of polarity in two adjacent umbrae of large spot-group of August, 1917.

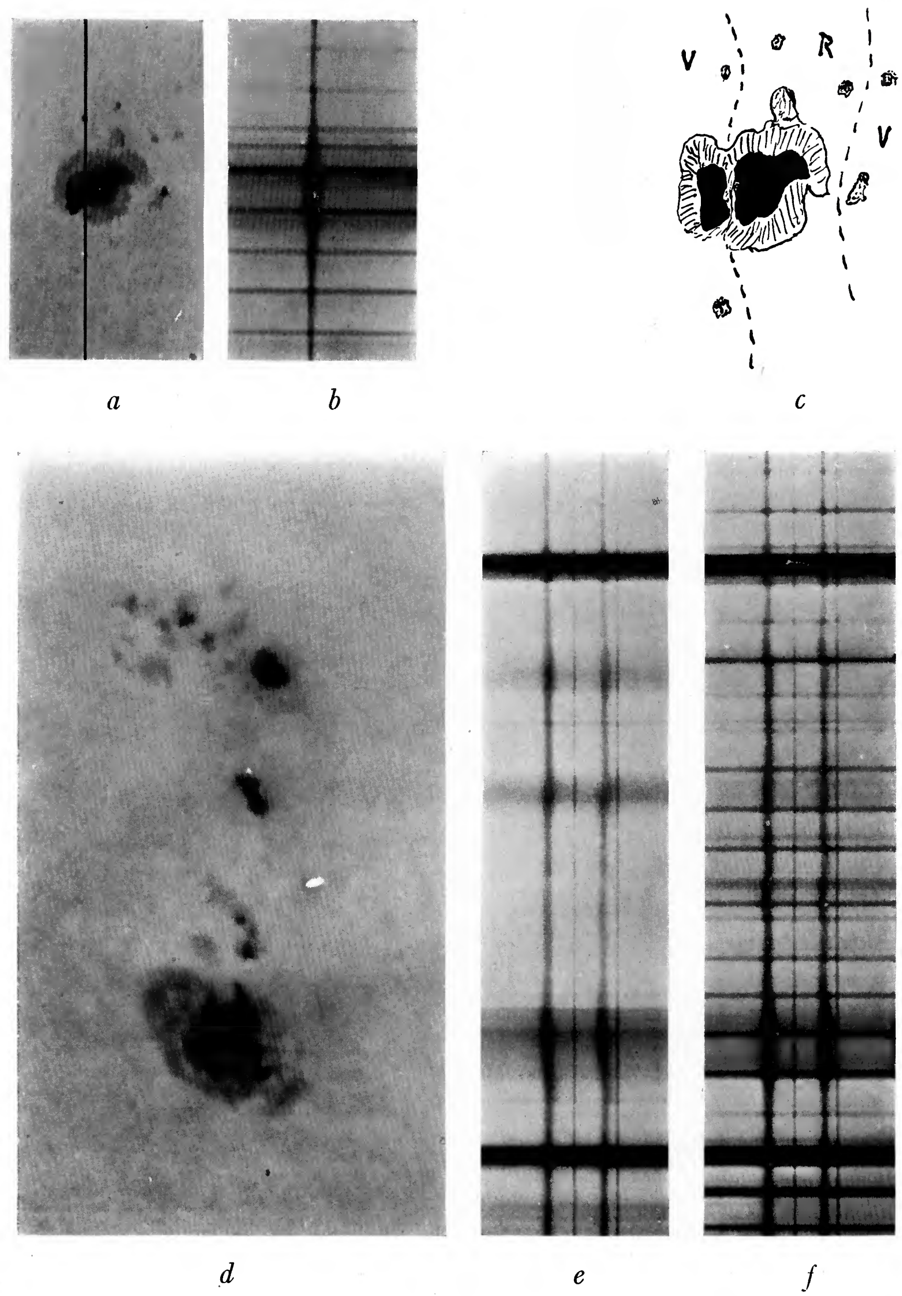
PLATE VI



PHOTOGRAPHS OF LARGE BIPOLAR SUN-SPOT GROUP

a, February 9; *b*, February 10; *c*, February 12; *d*, February 13; *e*, February 14, 1917, showing change in position of the neutral line with change in longitude of spot.

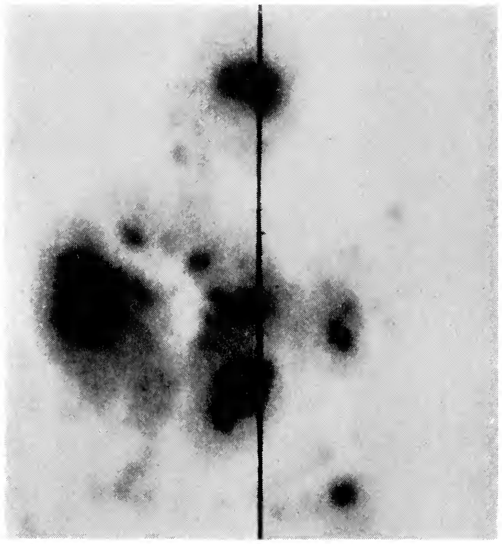
PLATE VII



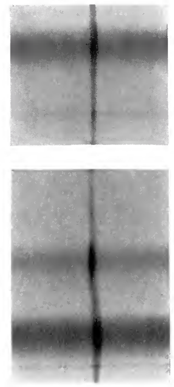
a, Sun-spot photographed March 9, 1916, in longitude W. 23°, the umbra divided by a bridge; *b*, iron triplet λ6173 observed with Nicol and compound quarter-wave plate, the slit occupying the position shown by the line in *a;* the nearly equal intensities of the *n*-components in the *same* strip of spectrum indicate the presence of two fields of opposite polarities; compare with Plate IV*i*, which shows the appearance when only a single field is present; *c*, sketch showing the distribution of polarities for other members of the group.

d, Bipolar sun-spot group photographed June 19, 1914; *e, f*, the iron lines λ 6301.7 and λ6302.7 as shown in the spectra of the three principal members of the group, with Nicol and (*e*, single; *f*, compound) quarter-wave plate; the configuration of the lines indicates that the two smaller spots are of the same polarity, but opposite to that of the largest spot.

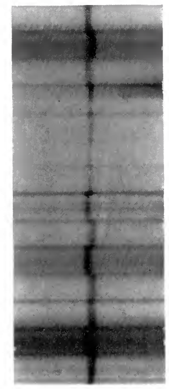
PLATE VIII



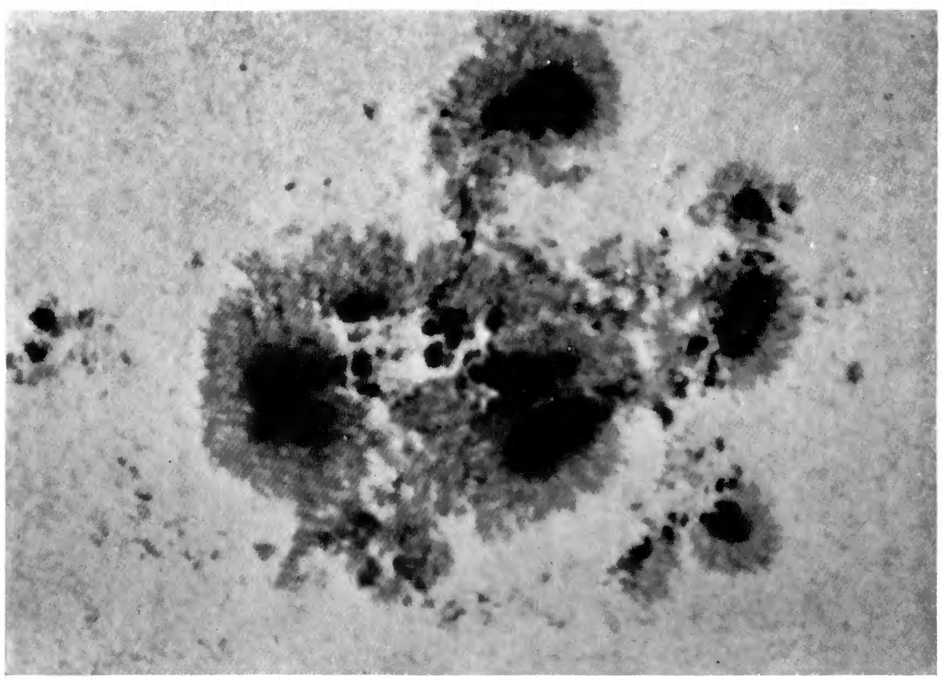
a



b



c

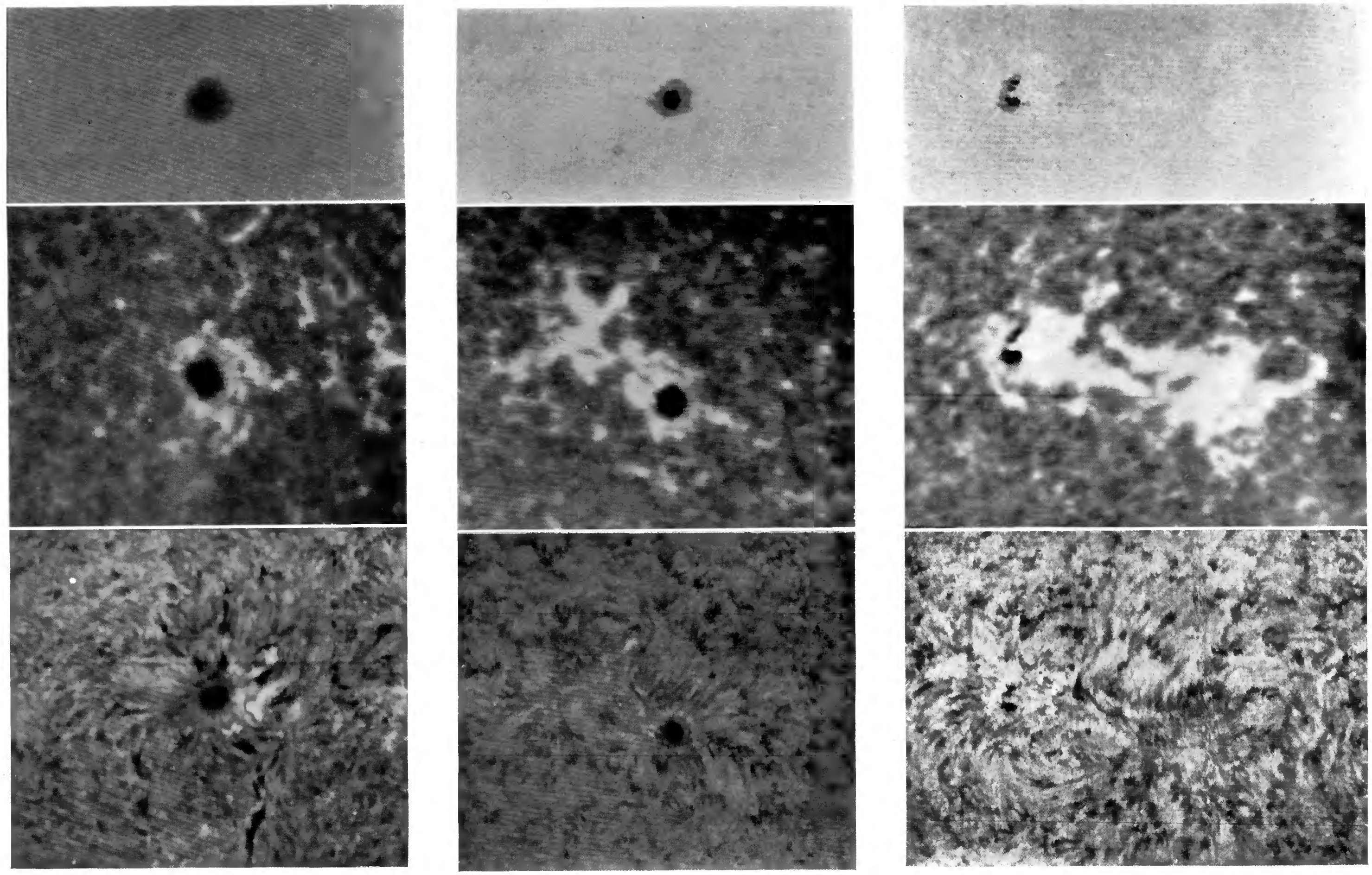


d

a, b, c, Photographic observations of a multipolar sun-spot group on August 8, 1917, similar to those described in Plate VII*d, e, f,* the spectral line in this case being the iron triplet λ6173; the lack of definition in *a* is due to poor seeing, together with the fact that it is a photograph of the image of the group formed by the 150-foot telescope, projected on a card mounted above the slit of the spectrograph.

d, An enlarged photoheliogram of the same group made with the 60-foot tower telescope on August 6, 1917, under good atmospheric conditions.

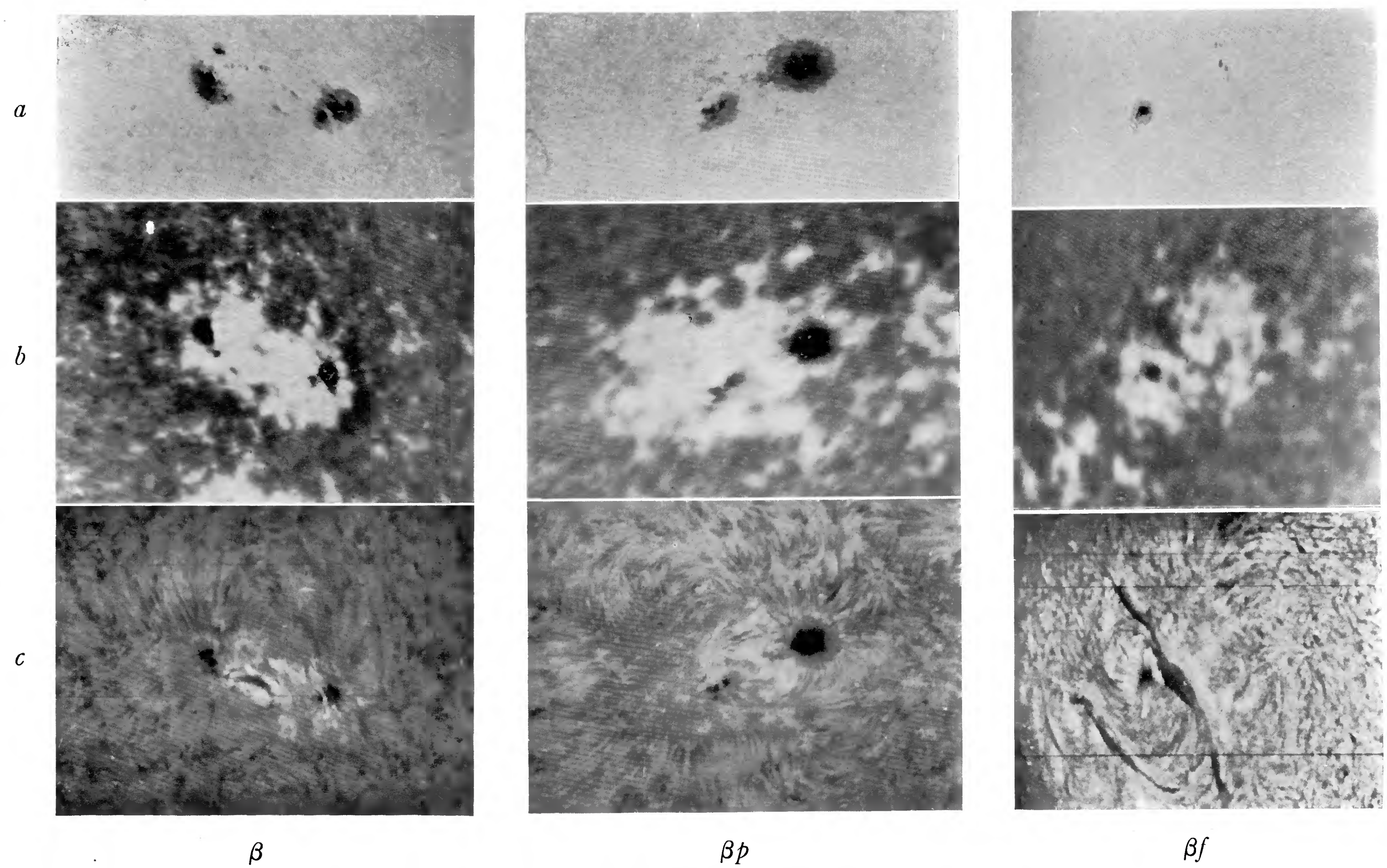
PLATE IX



CLASSIFICATION OF UNIPOLAR SUN-SPOTS

a, Photoheliograms; *b*, K_2 spectroheliograms; *c*, Hα spectroheliograms; **α**, September 3, 1915; **αp**, September 15, 1914; **αf**, September 15, 1914.

PLATE X



Classification of Bipolar Sun-Spots

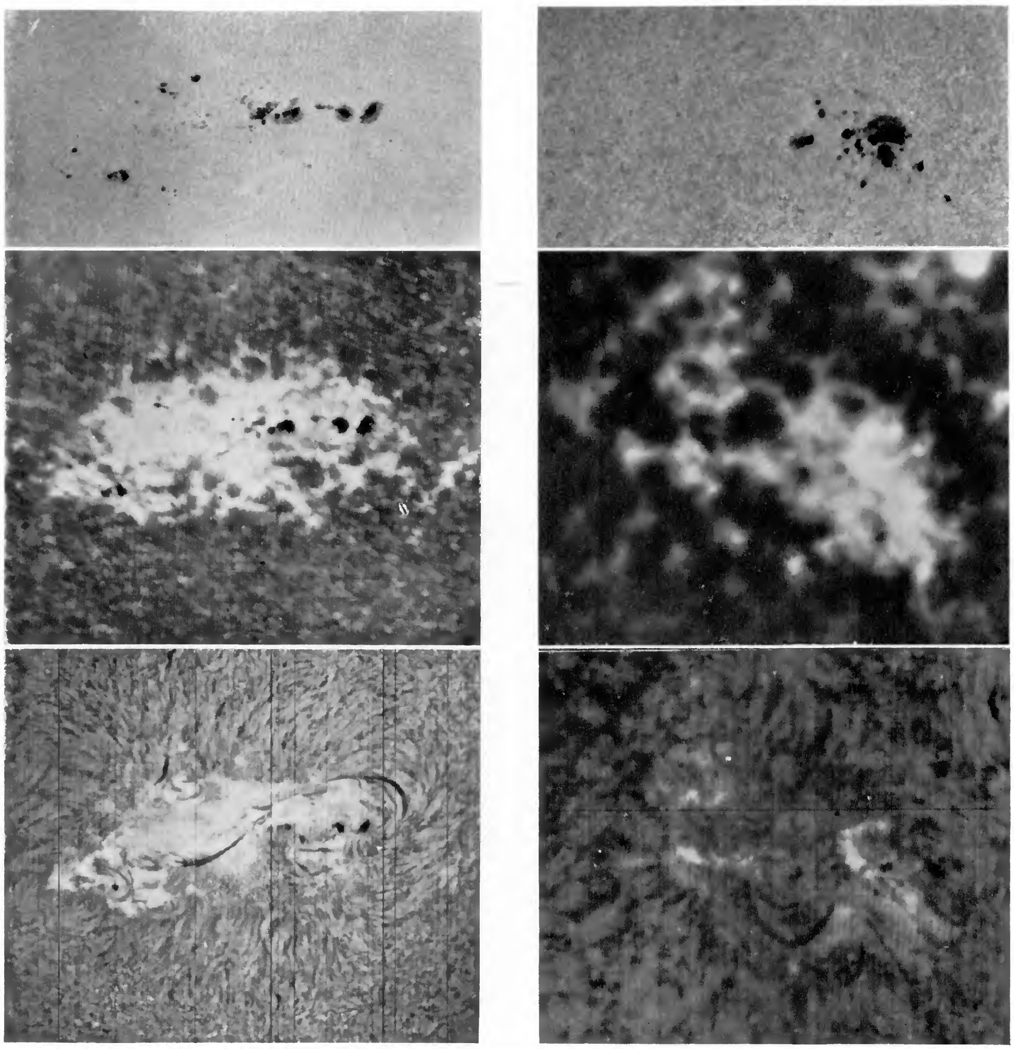
a, Photoheliograms; *b*, K_2 spectroheliograms; *c*, $H\alpha$ spectroheliograms; β, September 9, 10, 1909; βp, July 12, 1914; βf, April 22, 1916

PLATE XI

a

b

c



βγ γ

CLASSIFICATION OF MULTIPOLAR SUN-SPOTS

a, Photoheliograms; *b*, K_2 spectroheliograms; *c*, Hα spectroheliograms; $\beta\gamma$, an intermediate type, observed August 5, 1915; γ, July 25, 1917. Plate VIII*d* shows the photoheliogram of a large and unusually complicated γ group.