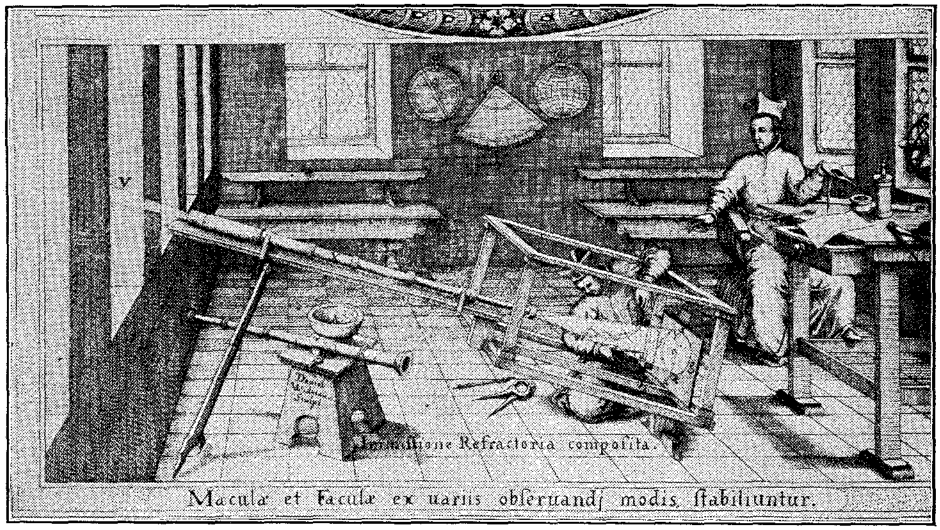


Fig. 1.—Small telescope used by Scheiner.

This illustration, copied from Scheiner's "Rosa Ursina," published in 1630, shows how sun-spots may be observed by projecting the solar image on a smooth white surface.

Sun-Spots as Magnets

BY GEORGE ELLERY HALE

Author of "The Depths of the Universe," "Barnard's Dark Nebulæ," etc.

ILLUSTRATIONS FROM PHOTOGRAPHS AND DIAGRAMS

SUN-SPOTS have been known since the third century of our era, though the western world held its belief in an immaculate sun until the invention of the telescope. The first edition of the great Chinese encyclopædia, published in one hundred volumes in 1322, contains observations of forty-five sun-spots made between A. D. 301 and 1205. In spite of our meagre indebtedness to China in the field of scientific research, there is no reason to doubt the authenticity of these observations, as the largest spots are easily visible to the naked eye when the brightness of the sun's disk is reduced by smoke or haze. It is strange, however, that their existence was not recognized in Europe.

It is also an odd coincidence, though certainly nothing more, that the phenomenon of magnetism, now known to be an invariable attribute of sun-spots, is said by many authorities to have been first recognized in China. In the second century B. C. a Chinese author wrote of "magnetic cars," which he claims were given more than nine hundred years before by the Emperor to the ambassadors from Tonkin and Cochin China, to guide them on their return journey across the desert. These contained a natural lodestone, floated on water, which pointed toward the south. According to this version, the magnetic compass, used also in China for the orientation of temples, was subsequently adopted by Chinese navigators, from whom its use spread to India and thence to the Mediterranean.

Whatever the facts—for the Chinese made no scientific study of the sun or of magnets—our knowledge of the nature of sun-spots may be said to begin with the observations of Galileo and his contemporaries in 1610, while the optical discovery that rendered possible the detection of their magnetic phenomena was not made until 1896.

HOW TO OBSERVE SUN-SPOTS

A very small telescope, or even an ordinary field-glass or opera-glass, will afford the reader a view of sun-spots at a time of solar activity. The safest way to observe them is to point the instrument at the sun and focus the eye-piece until a sharp image of its disk, several inches in diameter, is projected on a surface of smooth white cardboard held at a distance of from two to four feet. Fig. 1 shows how this was done by Scheiner, a contemporary of Galileo. The spots can easily be distinguished from specks on the eye-piece by noticing that they move with the sun's image. At present we are just emerging from a period of solar calm, during which no spots have been seen for weeks at a time. But a new cycle of activity has already begun, and a few spots are beginning to appear. The reader hardly needs to be warned that if he wishes to look directly at the sun with his telescope, field-glass, or opera-glass he must protect his eyes with the blackest of smoked glass, as the intensely bright image would otherwise seriously injure them.

However, the modern astronomer makes most of his observations on photographs, and the reader may enjoy the same privilege. Fig. 4 is a picture of the sun taken on Mount Wilson July 30, 1906, when two sun-spots were visible. On the following day these spots had changed in appearance and shifted their position on the disk. This shift in position is due to the sun's rotation on its axis, easily seen by observing the spots from day to day. Sometimes they form on the visible disk, and in other cases they are first detected, surrounded by bright regions called faculæ, at the east edge (or limb) of the sun, where they are brought into view by its rotation.

In the present article the strange law of the solar rotation cannot be discussed, but it may be mentioned that the sun does not rotate like a solid body, all parts of which move together. A spot near the equator completes a rotation (if it exists so long) in about twenty-five days, while one at 45° latitude takes about two and one half days longer to return to the central meridian. Nearer the poles the rotation period is still longer.

Mention has already been made of the fact that spots are not always equally numerous on the sun's disk. In 1913, as in 1923, there were very few spots visible, and the interval between these times of minimum solar activity is on the average about 11.1 years. If we plot a curve showing the number or total area of spots on the sun, we find the large fluctuations indicated in Fig. 2. The year 1917 was one of great activity, when many spots could be seen daily. In 1923 weeks sometimes elapsed without the appearance of a single spot.

These cycles of spottedness have another peculiarity. After a minimum, the first spots of a new cycle appear in high latitudes, occasionally as great as 45°. As the cycle progresses, and the spots increase in number, their average latitude steadily decreases, so that the few that appear near the minimum are all within about 15° of the equator. Thus the advent of spots at latitudes between 30° and 40°, which occurs before the low-latitude spots of the old cycle completely disappear, is always taken as a mark of the beginning of a new cycle. The steady contraction of these sun-spot zones in the course of the cycle is also shown by Fig. 2.

THE STRUCTURE OF SUN-SPOTS

If our telescope is large enough we can magnify the solar image sufficiently to give us a view of the structure of sun-spots. Fig. 3 is from a drawing by Langley, showing the exquisite details visible with a large telescope under the best atmospheric conditions. The enormous scale of the spot is suggested by the figure of the earth at the left. We thus realize that when speaking of solar storms we are referring to phenomena incomparably greater and more violent than anything experienced in our own atmosphere.

Terrestrial storms, whether widely extended cyclones, with moderate wind velocities, or the much smaller but far more destructive hurricanes or tornadoes,

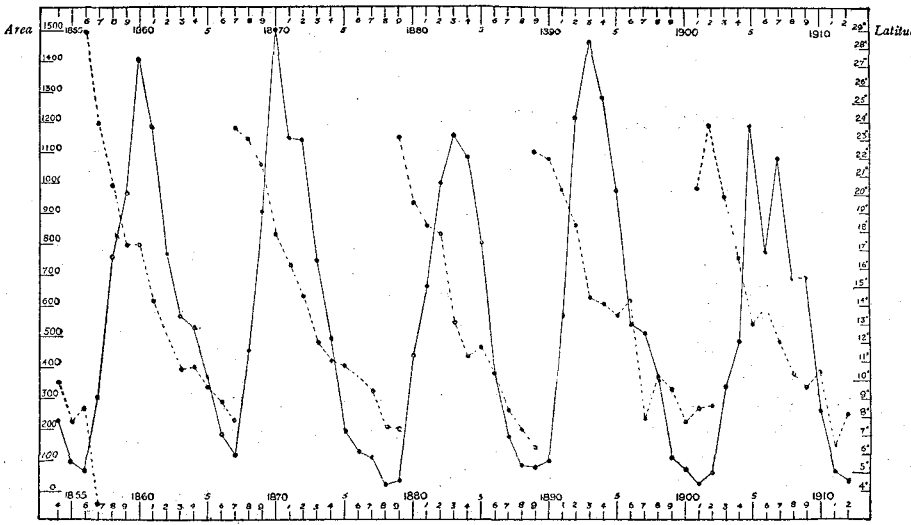


Fig. 2.—The periodic variation in the total area and mean latitude of sun-spots.

The continuous line represents the total area of spottedness, derived by Maunder from the Greenwich photographs. The broken line, giving the mean latitude of the spots for the different years, shows how each new cycle of solar activity begins in high latitudes during the minimum. (From "Splendour of the Heavens," Part III, page 112.)

are in general whirling storms, in which the air blows along spiral lines toward a centre. Seen by an observer looking down on them from above, the wind currents would invariably indicate a left-handed whirl in the northern hemisphere and a right-handed whirl in the southern hemisphere. The sun differs fundamentally from the earth in many respects, including its gaseous nature and its enormously high temperature, which shows no such difference between equator and poles as we see on the earth. But the terrestrial law of storms whets our curiosity as to the nature of solar storms and encourages us to seek for some definite law on the sun.

Sir John Herschel was perhaps the first astronomer to suggest that sun-spots may be vast whirling storms, analogous to terrestrial cyclones or tornadoes. In this belief he was later supported by the French astronomer Faye, but the observational evidence seemed to be against them. The great majority of sun-spots showed no indication of vortex structure, and when the presence of curved penumbral filaments occasionally suggested it, opposite curvatures in the same spot seemed to preclude the idea that a single great vortex was at the bottom of the disturbance. The result was that the most experienced observers could see no rational grounds for the vortex theory.

THE SPECTROHELIOGRAPH

In 1892, at the Kenwood Observatory, in Chicago, a new instrument was developed and thrown into the attack. This was the spectroheliograph, which will be described in its various forms in another article. Suffice it here to say that the purpose of the spectroheliograph is to give monochromatic pictures of the sun, in the light of a single gaseous constituent of the solar atmosphere. Thus a photograph taken with one of the two prominent calcium lines, H and K, at the violet extremity of the solar spectrum, reveals the immense luminous clouds of calcium vapor shown in Fig. 5. These are quite invisible to the eye, as we may see by comparing this image with that in Fig. 4, which is a photograph taken at nearly the same time in the ordinary way, without a spectroheliograph. The application of this new method, which makes possible the study of the solar atmosphere above and around sun-spots, might be expected to disclose the existence of definite currents or winds which would help to solve our problem.

But although the spectroheliograph

was systematically applied, and improved in various ways so as to permit horizontal cross-sections of the calcium clouds at various levels to be photographed, some years elapsed before much new information was gained as to the nature of sun-spots. Then hydrogen light, the use of which involves greater technical difficulties, was employed to disclose the hydrogen clouds at various levels. New and remarkable phenomena were discovered, but no clew to the enigma was found until the strong hydrogen line at the red end of the solar spectrum, known as Hα, was tried on Mount Wilson in 1908, when plates sufficiently sensitive to red light became available. This at once revealed another state of affairs, which prevails several thousand miles above the level seen in visual observations of sun-spots.

Fig. 6 tells no uncertain tale. It points unmistakably to the presence of two great vortices, whirling in opposite directions on opposite sides of the solar equator, and centring over two large sun-spots. These spots, as seen by the eye, were in no wise peculiar, and gave no more evidence of vortex structure than others before them. But the characteristic forms of the hydrogen images, repeated, in varying detail, day after day, was an index that could not be ignored.

Thus without pausing to puzzle over difficult questions of secondary importance, such as the exact relationship of the high level hydrogen structure to the spot below it, the vortex theory of spots was revived and another attack begun along a line suggested by new discoveries in physics.

ELECTRONS

The first conception of definite atomic charges of electricity was reached by Faraday in his electrochemical researches. It resulted from the fact that when a current is passed through a liquid a certain quantity of electricity moves from one pole to the other in association with a definite quantity of matter. The elementary charges visualized by Maxwell as "molecules of electricity" and called by Johnstone Stoney "electrons" when in the form of ultimate minimum units, are now recognized as common to all matter.

This began to appear in 1872, when Sir William Crookes announced the discovery of "a fourth state of matter." When the present writer lectured at the Royal Institution in 1909 on "Solar Vortices and Magnetic Fields," Sir William was kind enough to exhibit once more the very tube in which he had first shown this "fourth state of matter" in the same lecture-room. Following in the wake of Faraday and others, he had pumped out the gas from the tube until only one millionth of the original quantity was left. Through this he passed an electric discharge, appearing like a bundle of luminous rays, which he proved to consist of minute particles projected from the cathode or negative pole. These can be deviated from their straight path by a magnet and also by an electric field. They are thus shown to carry an electric charge, which Sir J. J. Thomson subsequently demonstrated to be that of the "corpuscle," or electron, which has a mass about one two-thousandth part of the mass of the hydrogen atom. The beautiful "oil-drop" experiment, by which Millikan measured the charge of these elementary units with unequalled precision, was one of the chief factors in determining the recent award to him of the Nobel prize in physics.

The experiments of Thomson and others soon proved that these negative electrons, associated in various numbers with positively charged particles of greater mass, not only constitute the atoms of all the elements but also are set free by high temperatures. They are present, for example, in all flames, and are emitted by highly heated solids and vapors. Thus they must exist in such bodies as the sun, where the temperature at the surface is more than 6000° Centigrade.

It is well known that by passing an electric current through a coil of wire a magnetic field is produced. We perform this experiment every time we touch a button to ring an electric bell. An electric current is now recognized to be merely a stream of electrons, and in a celebrated experiment Rowland produced a magnetic field by rapidly rotating an electrically charged plate. Thus the whirling of the electrically charged particles undoubtedly present in a sun-spot vortex should produce a magnetic field. If for any reason there were a sufficient preponderance of positive or negative charges (equal charges of opposite sign would merely counteract one another without producing a magnetic effect), the magnetic field in the sun-spot vortex might be of considerable intensity. But how could were accompanied, however, by a great number of widened lines, and this combination suggested, because of a discovery made by the Dutch physicist Zeeman, that the observed effects might in fact be due to the influence of the magnetic field called for by the vortex hypothesis. Before describing Zeeman's work, we may glance back at the earlier researches of

Fig. 3.—Langley's drawing of the sun-spot of March 5, 1873. (From "The New Astronomy.")
The scale is indicated by the figure of the earth in the upper left-hand corner.

it be detected at the distance of the earth?

This was the process of "guessing by hypothesis," to use an expression of Faraday's, employed to guide the tests made on Mount Wilson to determine the nature of sun-spots. It fortunately happened that while the spectroheliograph was being perfected at the Kenwood, Yerkes, and Mount Wilson observatories, another long series of experiments had made possible the photography of the spectra of sun-spots on a large scale. In these photographs certain double lines appeared, which had been seen by visual observers of sun-spot spectra and designated as "reversals," supposed to result from the superposition of vapors of different temperatures. These "reversed" lines

Faraday, who was the first to detect the effect of a magnetic field on light.

MAGNETISM AND LIGHT

The archives of the Royal Institution, which was founded in 1799 by the American Count Rumford, are rich beyond comparison in fundamental contributions to progress. Here in long and illustrious succession such leaders as Young, Davy, and Faraday have pushed forward the boundaries of knowledge and laid the foundations of modern science and industry. No documents in the history of civilization are more interesting than the original records of great scientific discoveries, found in extraordinary profusion in Faraday's note-books. Page after page discloses the essential germ of some prolific principle, such as the production of an electric current by moving a magnet near a coil of wire—the principle of the dynamo and the chief basis of modern electrical engineering. Such a discovery is so fundamental and so widespreading that it gives rise to innumerable ramifications, reaching into many fields of science and many aspects of life. In this article we can do no more than trace one of the ramifications of Faraday's great discovery of the effect of magnetism on light.

It came at the end of an exhaustive series of experiments, based upon a principle to which Faraday adhered with such tenacity that no discouragement could shake his faith in it.

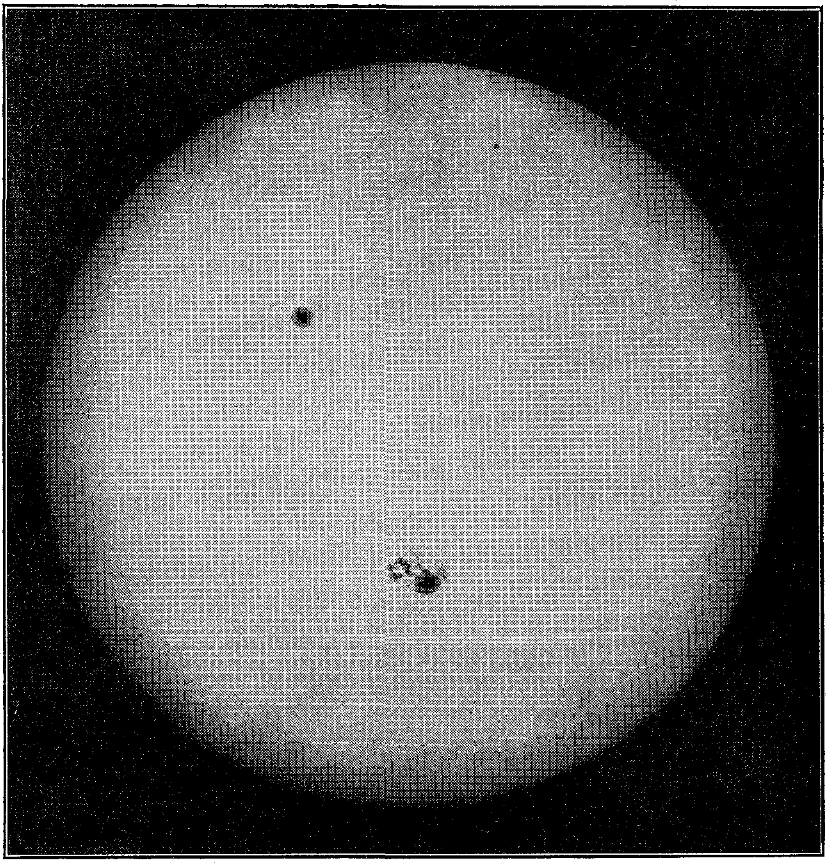


Fig. 4.—Direct photograph of the sun, July 30, 1906.

This was taken just before the calcium clouds in Fig. 5 were photographed, and shows the sun-spots lying below them.

"I have long held an opinion, almost amounting to certainty, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin, or, in other words, are so directly related and mutually dependent that they are convertible, as it were, one into another, and possess equivalents of power in their action."

Following this principle, which also guided him in many other researches, Faraday set up a powerful electromagnet, and endeavored to find evidence of the influence of its field on a beam of light passing near the poles. The light of an Argand lamp was polarized, or caused to vibrate in a single plane, by reflecting it from a surface of glass. After traversing the magnetic field it was examined through a Nicol prism, which permitted the plane of its vibrations to be determined.

Experiment after experiment ended in failure, showing no effect of the magnet, whatever the direction of the light with respect to its poles, or whatever the medium—air, many kinds of glass, Iceland spar, etc.—through which it was transmitted. Finally, when success seemed hopeless, the effect of some very heavy lead glass, made by Faraday many years previously in the course of certain optical experiments, was tried. The results may be given in his own words, copied from his original note-book:

"A piece of heavy glass (7485) which was 12 inches by 1.8 inches and 0.5 of an inch thick, being a silico borate of lead and polished on the two shortest edges—was experimented with. It gave no effects when the *same magnetic poles* or the *contrary* poles were on opposite sides (as respects the course of the polarized ray):—nor when the same poles were on the same side either with the constant or intermitting current.—BUT when contrary magnetic poles were on the same side there *was an effect produced on the polarized ray* and thus magnetic force and light were proved to have relation to each other. This fact will most likely prove exceedingly fertile, and of great value in the investigation of conditions of natural force."

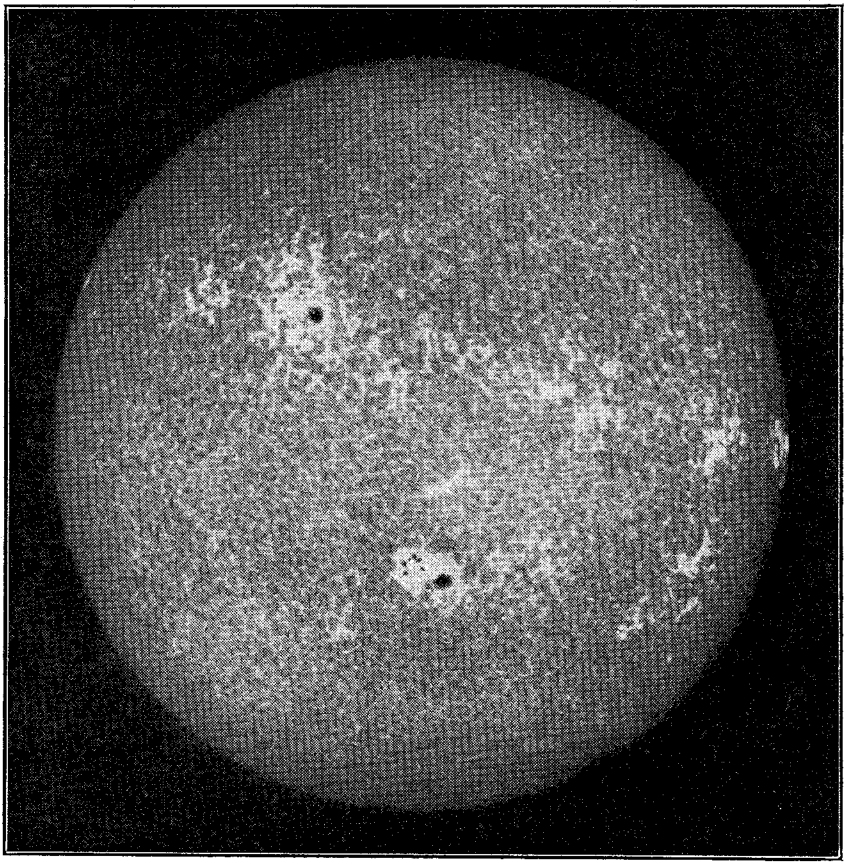


Fig. 5.—Luminous clouds of calcium vapor in the solar atmosphere.
Photographed with the 5-foot spectroheliograph of the Mount Wilson Observatory, July 30, 1906.

The effect thus produced was a rotation of the plane of polarization of the light, through an angle (measured by rotating the Nicol until the enfeebled light was restored to its former brilliancy) which increased with the length of the block of glass and the strength of the magnetic field. By reversing the direction of the current through the coils of the magnet, the direction of rotation of the polarized beam was also reversed. Subsequently it was found that this power of rotation was exhibited by many substances besides the heavy glass, including various liquids and also flint and crown glasses unsuccessfully tried in the first experiments.

RADIATION IN A MAGNETIC FIELD

This initial success, which had many important consequences, was obtained on September 13, 1845. On March 12, 1862, the last experiment recorded in Faraday's note-book shows how clearly he was still looking toward further possibilities. He had shown that a magnetic field can rotate a beam of polarized light passing through it from a luminous source outside of its influence. But could such a field affect the nature of the light emitted by luminous particles vibrating within it?—a very different problem.

Guided by the same unerring vision that astonishes us in every phase of Faraday's experimental researches, he placed sodium and lithium salts in a flame between the poles of a magnet and examined the lines of their spectra with the aid of polarizing apparatus. No effect was observed, however the experiment was varied. But the instinct of the great physicist was not at fault. For in 1896 Zeeman, of Leyden, aided by much more powerful apparatus, found that an intense magnetic field greatly affects the spectral lines of luminous vapors radiating within it. The influence of the field, missed by Faraday merely because his instruments were too feeble to show it, is such as to resolve lines normally single into from three to twenty-one components.

Zeeman's magnificent discovery, which now greatly aids the physicist in his interpretation of the nature of atoms and the constitution of matter, was stimulated by reading Faraday's notes on his last unsuccessful experiment, as quoted by Maxwell in his "Collected Works." Zeeman was fortunately able to use a Rowland concave grating spectroscope, far more powerful than Faraday's instrument. Between the poles of his Ruhmkorff magnet, also much superior to Faraday's, he placed the middle part of the flame of a Bunsen burner. The experiment is best described in his own words:

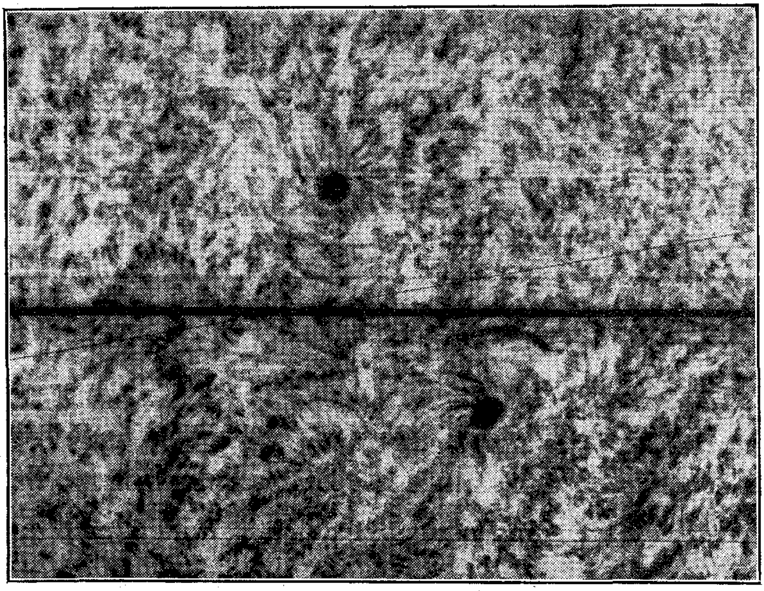
"A piece of asbestos soaked with common salt was put in the flame in such a manner that the D lines were seen as narrow and sharply defined lines on the dark ground. The distance between the poles was about 7 millimetres. If the current was put on, the two D lines were distinctly widened. When the current was cut off they returned to their original condition. The appearance and disappearance of the widening was simultaneous with the making and breaking of the current."

According to the theory of Lorentz, the electrons whose vibrations give rise to the D lines should experience forces which not only cause the lines to widen but actually split them up into several distinct components. Moreover, these components should be polarized in distinctive ways, permitting them to be extinguished or transmitted by a Nicol prism mounted before the split of the spectroscope, in some cases in conjunction with a mica plate or Fresnel rhomb. Guided by this theory, Zeeman was able to break up spectral lines into several components and to obliterate these at will with his polarizing apparatus.

THE TEST APPLIED TO SUN-SPOTS

Thanks to this discovery, and to the recent completion on Mount Wilson of the sixty-foot tower telescope, the means for testing the vortex hypothesis of electromagnetic fields in sun-spots lay ready at hand. This instrument forms an image of the sun about 6.7 inches in diameter in a laboratory at the base of the tower, beneath which a grating spectroscope, 30 feet in length, is mounted in a well. By bringing the image of a sun-spot upon the narrow slit of the spectroscope, and holding it there by the driving clock of the cœlostat at the summit of the tower, the thousands of lines in its spectrum can be studied either visually or photographically. As already remarked, most of these lines were already known to be widened and a few had been found to be double or triple. But such peculiarities can be caused in various ways that have nothing to do with a magnetic field. A searching test must therefore be applied, which would settle the question beyond the possibility of a doubt.

Sun's



equator.

Fig. 6.—Right and left handed hydrogen vortices, on opposite sides of the solar equator.

The hydrogen atmosphere above sun-spots, photographed with the spectroheliograph at Mount Wilson on October 7, 1908. These spots were found to be of opposite magnetic polarity.

Fortunately, the unique characteristics of the Zeeman effect can be identified with complete certainty if the magnetic field that produces them is strong enough. Iron lines in the laboratory, when the luminous vapor emitting them is acted on by a magnet, are split into three or more components, polarized in distinctive ways which vary with the angle between the direction of observation and the direction of the magnetic field. Without going into the complex details of the polarization phenomena, we may say in general that under such conditions as we should expect when a spot is near the middle of the sun, the central component of triple lines in its spectrum, if produced by a magnetic field, should be plane-polarized and the two outer components elliptically polarized in opposite directions. Both in the number of its components and in the character of the polarization phenomena, each iron line in the spot must match its counterpart in the laboratory. Moreover, all of the other elements present in the spot—sodium, calcium, chromium, titanium, manganese, nickel, cobalt, etc. —must be no less consistent than iron; each line of each element must behave precisely as it does under similar conditions in the laboratory.

No time was lost in making the test, as the special apparatus required for the study of the Zeeman effect, including Nicol prisms, a Fresnel rhomb, and a large magnet for laboratory investigations, were available to supplement the tower telescope and its spectrograph. Two iron lines in the red part of the sun-spot spectrum, both of which were greatly widened, while one appeared to be a triplet, were first examined. The first day's observations were inconclusive. But on the second day, in the third-order spectrum, definite results were obtained. A Nicol prism and Fresnel rhomb were mounted above the slit. When the Nicol was set at a certain angle, the red component of the triplet was cut off, the violet one remaining. By turning the Nicol 90°, the violet component was cut off and the red component reappeared. Other lines gave similar effects, and all of the widened lines were affected precisely as in Zeeman's original experiment. When observed with the large magnet in the laboratory, each line behaved as it did in the sun. It soon became certain, after many searching trials, that magnetic fields existed in all sun-spots examined.

WHIRLS AND COUNTER-WHIRLS

Limitations of space preclude a description in the present paper of our studies on the nature of the sun-spot vortex. We must fix our attention here on a single application of the magnetic method, which has given a partial answer to our question regarding a possible analogy between the laws of terrestrial and solar storms.

Fig. 6, showing two solar vortices whirling in opposite directions on opposite sides of the sun's equator, is temptingly like the terrestrial case. The opportune appearance of these spots seemed to offer the means for a crucial test of the electromagnetic vortex hypothesis, which was immediately applied. They also prepared the way for a long investigation which has finally given us a law of sun-spot polarities.

Fig. 8A represents a zinc triplet, observed in the laboratory along the lines of force, through a hole in one of the pole pieces of the magnet. In this case the central component of a triplet completely disappears, and either of the side components can be extinguished at will with a Nicol prism and quarter-wave plate. In a sun-spot the central component is almost always present, because we cannot often look exactly along the lines of force, and usually get an effect like Fig. 8B, which shows the zinc triplet as seen at an angle of 60° with the lines of force. But either of the side components can be extinguished, just as in the laboratory.

Returning to the test with the magnet, and assuming that only one component of the triplet is visible, let us observe the effect of reversing the direction of the current flowing through the coils. The instant the current is reversed the component previously visible disappears and the other component comes into view.

The same thing occurred in the two sun-spots. With the polarizing apparatus unchanged their spectra were photographed in immediate succession. The right component of the iron line appeared alone in one spot, the left component in the other. Assuming the spot vortices to be whirling in opposite directions, like the hydrogen vortices above them, our electromagnetic hypothesis supposes that charged particles are whirling clockwise in one spot, counter-clockwise in the other. The coils of the magnet, into which we look just as we look into the vortex coils of the spot, carry the streaming electrons of the current. When we reverse the current we cause them to flow in the opposite direction. Thus the presence of one or the other component of the iron line, to the red or violet as the case may be, provides a quick and decisive index to the polarity of the spot.

It is true that we cannot yet tell with certainty the sign of the electric charge in the spot vortex, whether positive or negative. Until this is learned we cannot say whether the spot vortex whirls clockwise or counter-clockwise.* But we can say that two spots showing opposite components of the iron triplet are of opposite polarity, and we can also identify the polarity of each, fixing it as a north-seeking pole or a south-seeking pole. A study of the magnetic observations of a large number of spots may thus lead to a law of sun-spot polarities.

BIPOLAR SUN-SPOTS

As already remarked, such photographs as that reproduced in Fig. 6 at first tempted us to believe that the law of sun-spot vortices is the same as that of our cyclones and tornadoes, which whirl clockwise in one hemisphere, counter-clockwise in the other. We soon found, however, that spots of opposite polarity, presumably representing vortices whirling in opposite directions, occur in the same hemisphere of the sun. This com-

* The hydrogen vortices shown in Fig. 6 represent a higher level in the solar atmosphere and do not necessarily whirl in the same direction as the low-lying spot vortex. The nature of the hydrogen vortices and their relationship to the spots below them will be discussed in a later article on the remarkable phenomena of the solar atmosphere.

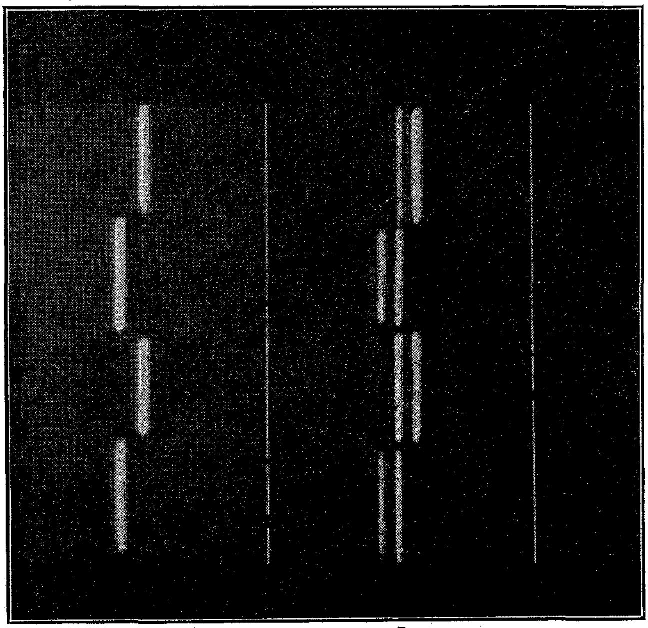
Fig. 7.—Michael Faraday in 1857, showing the heavy glass with which he discovered the action of magnetism on light.

plicated the problem, but a decisive discovery then prepared the way for an effective attack.

In the earliest drawings of Galileo and Scheiner, and in those of all subsequent observers, we find many spot groups depicted as pairs, or as long streams of spots lying nearly parallel to the solar equator. The spot drawn by Langley (Fig. 3) is one of this type. Magnetic observations of such groups showed us that in almost every case the spots of a pair, or the clusters of spots lying at opposite ends of a stream, are of opposite polarity. Occasionally, it is true, the spots of these groups are so mixed that no sign of order can be detected. But some 60 per cent of all spots may be classified without hesitation as definite bipolar groups.

Of the remaining single spots, or closely clustered groups of spots of the same polarity, about 30 per cent are either preceded or followed by a train of faculæ or flocculi, in which a second spot, of opposite polarity, sometimes appears intermittently. This peculiarity led to a search for invisible spots, which have been detected in the following way:

On account of the weakness of the field in small vortices, their existence can be disclosed only by an extremely small widening of certain lines in the spot spectrum. A minute moving object is more easily seen than a fixed one, so the slight widening is caused to appear alternately on each side of the line, by means of a special polarizing device oscillating back and forth across the slit of the spectroscope. In this way weak magnetic fields have been found in masses of faculæ or flocculi, usually preceding or following single spots. Sometimes these incipient spots, after observation in their invisible state for two or three days, have become visible, only to disappear later, when their presence as vortices has again been detected by their magnetic effect. Thus we now have a means of studying sun-spots in their embryonic and post-mortem stages.



A B

Fig. 8.—A zinc triplet, photographed in the laboratory, (A) along the lines of force and (B) at 60° with the lines of force. In both cases the side components to red and violet are transmitted by alternate strips of the compound quarter-wave mica plate, used with Nicol prism before the slit of the spectroscope.

The discovery of invisible spots strengthens our system of classification, which treats single spots as the preceding or following members of incomplete bipolar groups. The disposition of the calcium flocculi behind or in front of the spot, as revealed by the spectroheliograph, determines the classification.

We conceive of a sun-spot on the vortex hypothesis as a region in which the luminous gases, cooled by the expansion caused by centrifugal action, appear as a darkened cloud upon the brilliant photosphere. Proof of this cooling is given by spectroscopic observations, which show changes in the relative intensities of lines due to reduced temperature and also the presence of such compounds as titanium oxide and magnesium hydride, the constituents of which occur uncombined in the hotter parts of the sun's atmosphere. It is easy to imagine the existence of vortices in which the cooling due to expansion is insufficient to produce a perceptible darkening of the photosphere. Such vortices may nevertheless give rise to magnetic fields detectible by the Zeeman effect.

THE DAILY POLARITY RECORD

Prior to the sun-spot minimum of 1913 our attention was chiefly concentrated on a few of the largest spots, in which the various complex manifestations of the Zeeman effect were studied. With the sixty-foot tower telescope and thirty-foot spectrograph then in use, the smaller spots were beyond the range of observation, and no extensive investigation of polarities was undertaken. The success of this telescope, the first of its kind, led us to design and build a much more powerful instrument of the same type, with which the polarities of all spots on the sun are recorded daily.

The familiar equatorial telescope, with its moving tube, is limited in length and unable to carry the very long spectroscopes needed for solar research. A series of investigations, beginning at the Kenwood Observatory in 1891 and continued with the forty-inch refractor of the Yerkes Observatory, led to the construction of the Snow horizontal telescope, with which the vortices in the solar atmosphere were discovered, and subsequently to the development of telescopes of the tower type.

The 150-foot tower telescope, completed in 1912, consists of a cœlostat and second mirror at the summit of a tower, which receive the sunlight and reflect it vertically downward to a twelve-inch objective of 150 feet focal length, mounted just below them. This forms an image of the sun about 16½ inches in diameter in a laboratory at the foot of the tower. Any part of this large image, such as a small sun-spot, can be held indefinitely on the slit of a powerful spectrograph, 75 feet in length. Through the slit its light descends into a well about 80 feet deep, excavated in the rock beneath the tower. Near the bottom of the well, after being rendered parallel by a six-inch lens, the rays fall upon a plane surface of polished speculum metal, ruled by a diamond point with lines at the rate of about 14,000 to the inch. This grating decomposes the white light into its constituent parts and sends it back through the lens, which forms an image of the resulting spectrum beside the slit in the room at the base of the tower. So great is the dispersion that the light which descends through a slit only three-thousandths of an inch wide is returned as a spectrum about 40 feet long, from red to violet. This is the spectrum of the second order, in which the polarity observations are made. Fig. 9 shows the iron triplet λ6173, as photographed in a sun-spot with this spectrograph. Observations of this line in all sun-spots give a daily record of their polarity and field strength.

THE LAW OF SUN-SPOT POLARITIES

Sun-spots were on the wane from the beginning of this work in 1908 until the minimum of activity in 1913. During this period only twenty-six spot groups

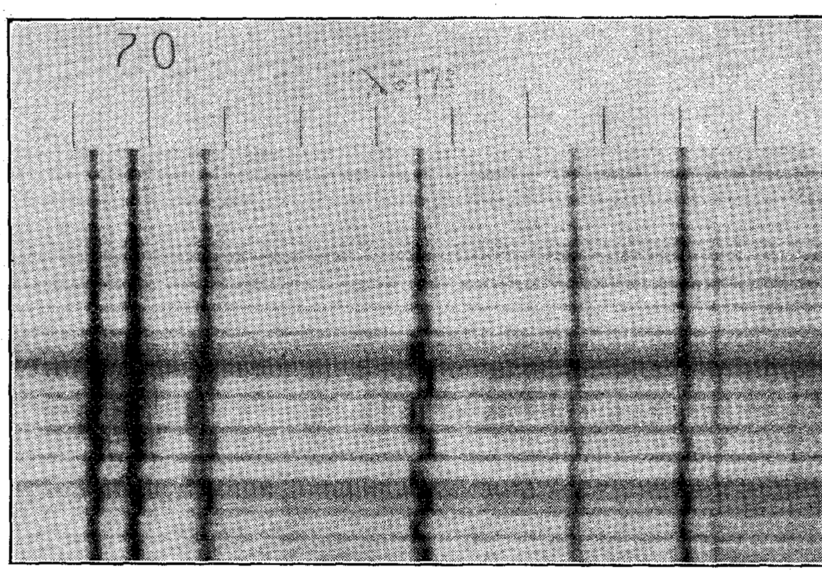


Fig. 9.—The Zeeman triplet λ6173 in the sun-spot spectrum.

Photographed in the second-order spectrum of the 75-foot spectrograph of the 150-foot tower telescope. The polarity of the spot is determined by the transmission of the red or violet component of the triplet by the "marked strip" of the compound quarter-wave plate.

were observed magnetically, but these sufficed to reveal the polarities then characteristic of the northern and southern hemispheres. With but two exceptions, all of these groups showed that preceding spots in the northern hemisphere were of south polarity (with south-seeking poles), while their following spots were of north polarity. In the southern hemisphere the order was reversed—preceding spots were of north, following spots of south, polarity.

This rule persisted in 1912, when the few spots at the end of the old cycle, in harmony with the ordinary law, were still appearing at infrequent intervals near the equator. The first small spots of the next eleven-year cycle then began to break out in high latitudes, and to our surprise their polarities were found to be reversed. Since that time, with the superior advantages afforded by the 150-foot tower telescope, the magnetic fields of 2,110 spot groups of this cycle have been observed, chiefly by Ellerman, Nicholson, Joy, and Pettit. After excluding the small number of spots that cannot be classified we find that all of these groups, with only 4 per cent of exceptions, follow this new rule: preceding spots in the northern hemisphere have north polarity, while preceding spots in the southern hemisphere have south polarity. Some extraordinary change had occurred in the sun, which on the most plausible interpretation could mean nothing less than a reversal in the direction of whirl in sun-spot vortices.

Under these circumstances we naturally looked forward with keen interest to the next sun-spot minimum, which has now arrived. As the cycle progressed the average latitude of the spots steadily decreased, finally bringing us back to conditions resembling those of 1912, with small and infrequent spots appearing near the equator. Spots announcing a new cycle sometimes develop as much as two years before the minimum, and in this case the first one was found on June 24, 1922, at 31° north latitude. It was a small single spot, but seemed to be a pre-

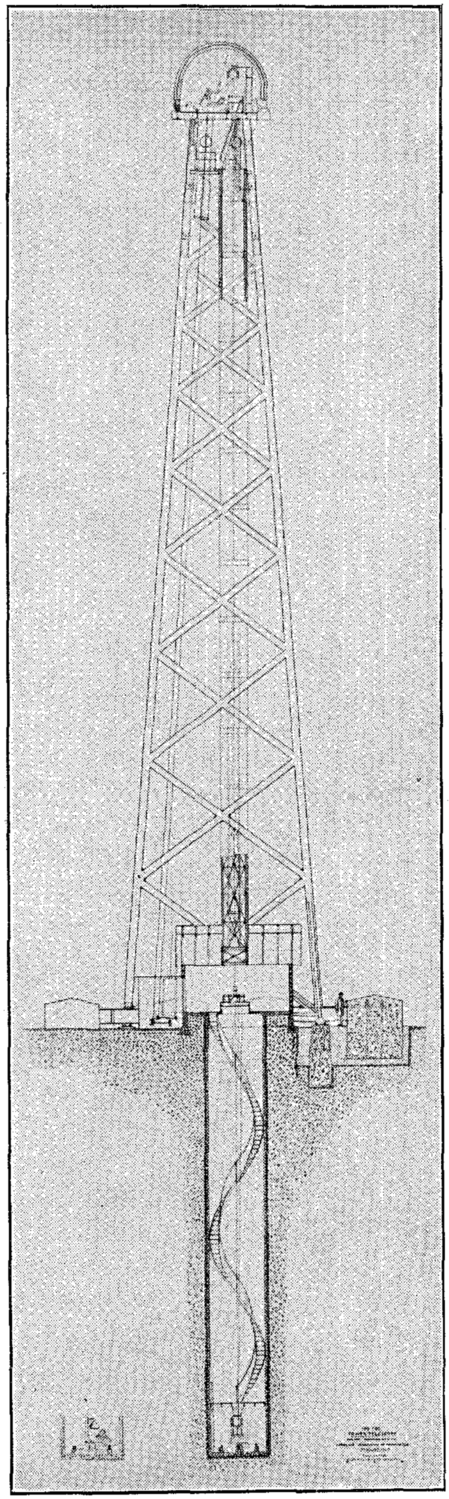


Fig. 10.—The 150-foot tower telescope of the Mount Wilson Observatory.

A spectrograph of 75 feet focal length, mounted in a well beneath the base of the tower, is used daily to determine the magnetic polarity and field strength of all sun-spots seen on the 16.5-inch solar image.

ceding one, and its observed polarity was south, corresponding to that of preceding spots in the northern hemisphere during the cycle ending in 1913. Another reversal of polarity was thus foreshadowed.

Since that time a number of spots of the new cycle, including some fine bipolar groups, have developed in high latitudes, while the low-latitude spots have practically ceased to appear. The new spots completely confirm the expected magnetic reversal, and give us the polarity law expressed graphically in Fig. 11. As the curves indicate, the polarities of the great majority of spots, opposite in the northern and southern hemispheres, remain the same throughout the eleven-year period and suddenly reverse with the renewal of activity in high latitudes. Thus the spots of alternate cycles are alike magnetically, and a period of about twenty-two years elapses between the successive appearances of similar spots. In one sense this may be regarded as the true sun-spot period, as it is the interval between successive returns of the sun to the same state. But the old period of about eleven years correctly represents the fluctuation in number and area of all spots, counted without regard to their magnetic character.

The conditions existing at successive minima, when two spot zones of opposite polarity coexist in each hemisphere for about two years, are shown in Fig. 12. There seems to be no terrestrial analogue for the combination of right and left handed vortices in pairs, as in bipolar spots; for the temporary occurrence in each hemisphere of two storm zones characterized by opposite directions of whirl, such as we see in Fig. 12; or for the gradual descent in latitude and the periodic reversal in the direction of whirl illustrated in Fig 11.

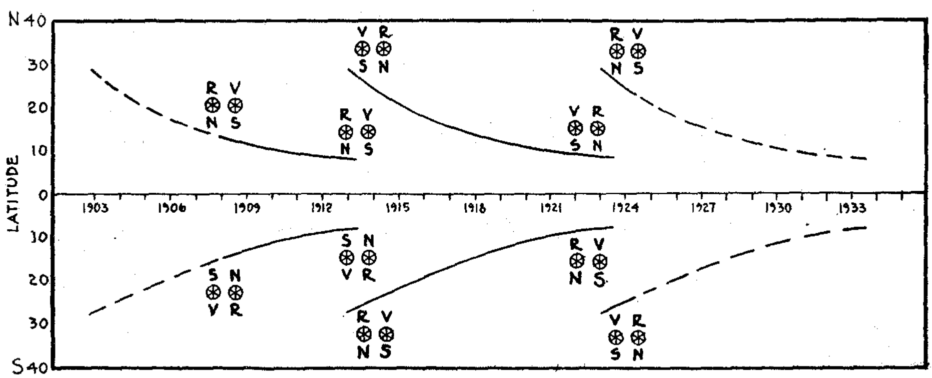


Fig. 11.—The law of sun-spot polarity.

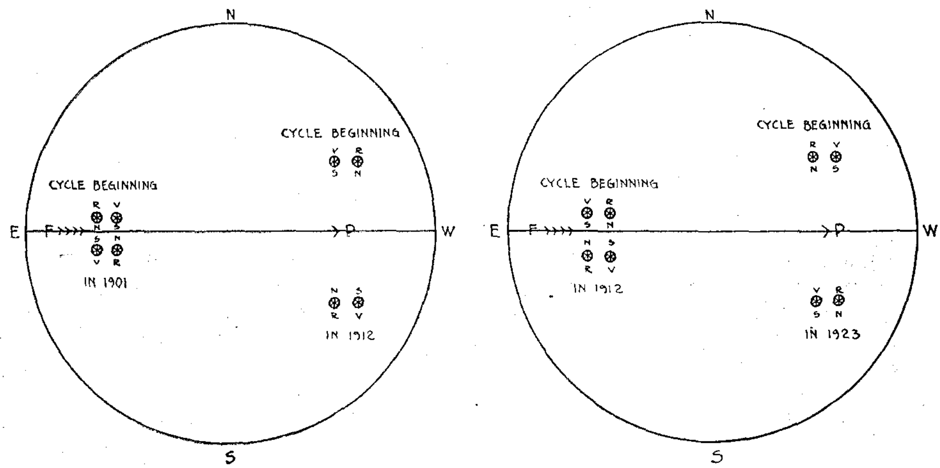
The curves show the approximate variation in mean latitude and the corresponding magnetic polarities of 2,110 sun-spots observed at Mount Wilson from 1908 to 1923.

TERRESTRIAL AND SOLAR STORMS

But why, it may be asked, may we not regard the vortices of bipolar spots as whirling in the same direction, and account for their opposite polarity by supposing the dominant electric charges in each to be of opposite sign? We do not yet fully understand the mechanism of the process that separates the positively and negatively charged particles in the sun and causes one or the other to dominate in a spot vortex. In thunder-storms, as Simpson has shown, the separation of electricity is probably due to the violent disruption of rain-drops or the collision of hail with snowflakes. As the conduction of the atmosphere is low, the wide separation of electricity necessary to give a lightning flash is possible. The conditions are very different on the sun, because of the high temperature and the conductivity of the gaseous atmosphere, and we certainly have no evidence that the charges in the two spots of a bipolar group are of opposite sign. If such could be the case, it would be difficult to show how this sign could depend upon the hemisphere, the latitude, or the spot cycle, not to speak of other objections. Difficult as the hydrodynamical problem involved in the alternative view may appear, it seems far easier to suppose that the dominant charge is the same in all solar vortices and that the polarity is determined by the direction of whirl.

But why should this vary in the remarkable way indicated by our observations? Even the association in pairs of vortices whirling in opposite directions is not easy to explain, though both theory and experiment agree in showing that a columnar vortex, extending deep into the sun, may turn up to the surface to form a half-ring vortex. This might account for some very simple bipolar spots, but many complex groups seem beyond the range of this attractive hypothesis. The periodic reversal of the direction of whirl, which evidently depends upon the ebb and flow of solar activity that marks the sun-spot cycle, remains as the crucial problem. The very nature of the sun itself seems to be involved, and with it, perhaps, the nature of other dwarf stars.

The traditional explanation of the direction of whirl in terrestrial cyclones, which dates from an early period, is a very simple one. Suppose a region of low pressure to occur at some point in the northern hemisphere. The wind rushing toward the depression from the south carries with it the higher moment of inertia of the atmosphere in the equatorial region, and its velocity must increase and deflect the air to the east of the meridian from which it started. The air descending from the north acquires a lower velocity and is deflected to the west. Hence the left-handed whirl. In the southern hemisphere, as a moment's reflection will show, a right-handed whirl would be produced under similar conditions.



Minimum of 1913.

Minimum of 1923.

Fig. 12.—Sun-spot zones during the minimum of solar activity.

Two zones in each hemisphere, in which the spots are of opposite polarity, exist for about two years at the time of each sun-spot minimum.

This explanation has been questioned in recent years, and it certainly does not suffice to account for the complex vortex phenomena of sun-spots. We now find (though the investigation is still far from complete) that the direction of whirl of the inflowing vortices shown by the spectroheliograph in the hydrogen atmosphere above sun-spots apparently does not depend upon the polarity of the corresponding spots or reverse in direction at sun-spot minima. Indeed, these vortices seem to be secondary phenomena, induced above spot vortices, which appear to lie at a much lower level, below the photosphere. Moreover, no sign of any radical change in the circulation of the solar atmosphere, such as the reversal in the direction of whirl in spot vortices would surely involve if they were high-level phenomena, has been detected. The peculiar law of the solar rotation persists without known change through the spot minimum, and all the evidence seems to favor the view that sun-spots are deep-seated manifestations of the internal circulation of the sun. In these mysterious depths we should therefore seek for the origin of sun-spots, the nature of their characteristic cycle, and the cause of the periodic reversal of their magnetic polarity.

"Not Poppy——"

BY McCREADY HUSTON

Author of "His," "Fairer Greens," "Jonah's Whale," etc.

ILLUSTRATION BY EUGENE C. CASSADY

TEN years passed before Carver Squires could bring himself to go home, and then his swift rush eastward was not in obedience to a new judgment of his case, but to a sudden numbness and bewilderment when, driving through a part of Indiana new to him, he caught a quality in the air from the fields and a certain blending of tones in the coloring on a hillside that brought the foothills back to him with an urge that even good sense, painfully acquired and long drilled, could not resist.

Now that he was home he was restless and distrustful of his action. Unquestionably he would have to flee again; would have to undergo all over the searing labor of obliteration that had made him look more than thirty-seven. His return was his first yielding to desire in ten years. He had thought he was in full control. Descending from the local train that had carried him the fifty miles south into the hills from the city where he had changed from the West, he had, with a grim smile, admitted to himself that the scent and colors of the hills were not the only reasons for his coming. Squires prized unmixed, true emotions; things a man could trust; senses which would not betray him. He was nettled, then, even irritated, to discover that twelve hours on trains with his thoughts—which would wing homeward ahead of him—had forced him to the admission that Annice Moray—she was Vaness now—was, after all, at least part of the drawing force he had ascribed to the hills of home.

Looking from his window at the Big Savage Country Club next day he decided that the best thing he could do would be to borrow somebody's car, go for a slow, luxurious drive among the hills, and take the night train away. The club—it was a surprise for him to find it—was a note of the new day in the old town. Standing undetermined on the station step and surveying with aversion the old hotel across the street, he had been found by Howard Graham, a remote cousin, and urged to put up as a guest at the club. It fitted in; and Graham was not likely to be a troublesome host. So, instead of the precarious services of the hotel, comforts—more comforts than he desired—were at his disposal in a country club-house which invited nothing but rest.

The first moment after his rising had been memorably perfect as he stood at his window, gazing across the State Highway at the sweep of the golf course toward the Notch, miles away. The second moment had suggested to him sharply that he had better go, immediately.

The first person he saw on the lawn below was Jerome Vaness.

The curious thing about it was that Vaness did not look any older. Squires turned abruptly and regarded his own face, and particularly his graying hair, in the mirror. Then he looked out again at