Solar Magnetism

By Dr. George E. Hale, For. Mem. R.S., Mount Wilson Observatory, Pasadena, California

THE recent celebration of Prof. Zeeman's seventieth birthday offers a favourable opportunity to describe current applications of his powerful method of research to the study of solar magnetism. Our latest results include the completion of the first observed 23-year magnetic cycle of sunspots and the conclusion of a long investigation of the sun's general magnetic field, made for the purpose of checking beyond question the original measurements begun in 1912.

Zeeman Effect in Sunspots

As explained eleven years ago in NATURE[1], I was led in 1908 to the discovery of magnetic fields in sunspots by a hypothesis based upon the results of two series of studies, begun at the Kenwood Observatory in 1890, and continued at the Yerkes and Mount Wilson Observatories. The first of these related to the nature of various phenomena of the solar atmosphere revealed by spectrographs and spectroheliographs. The hydrogen flocculi, as first shown by the $H\alpha$ line at Mount Wilson in 1908, indicated the existence of immense vortices surrounding sunspots, and suggested that electrically charged particles might be whirled within the spots in such a way as to produce appreciable electric currents. Such currents would set up magnetic fields, possibly of sufficient strength to be detected by a powerful spectroscope. Zeeman had shown how the spectrum lines of luminous metallic vapours between the poles of a magnet are widened or split into several components, polarised in distinctive ways. Meanwhile our studies of sunspot spectra, supplementing those made with less powerful spectrographs by Young, had reached a point where many lines on our photographs were not only widened but also separated into apparent doublets or triplets. These had previously been regarded as reversed lines, due to the superposition of two vaporous layers of different temperature and density. Such reversals actually exist in certain cases, notably in the lines of hydrogen and calcium. Thus, the true understanding of the sunspot spectrum had been obscured.

In the hope of disentangling the question, a new attack on sunspots was begun. Aided by the 60-foot tower telescope on Mount Wilson, equipped with a 30-foot grating spectrograph and suitable polariscopic apparatus, it was easy to test my hypothesis. The presence of magnetic fields was readily established in all the sunspots observed, and the polariscopic phenomena of the sunspot lines, varying as the solar rotation changed the angle between the lines of force and the line of sight, was quickly found to harmonise with Zeeman's laboratory results on the spectra of vapours. My solar work was greatly facilitated by experiments made in our own laboratory by King, provided with a Du Bois magnet and all the essential equipment.

Magnetic Polarity of Sunspots

The sunspot spectrum contains many thousands of lines, and its complete investigation is an extensive task. After a sufficient number of these lines had been examined in order to establish the existence, strength and general character of the magnetic fields, another phase of the problem was attacked.

Speaking broadly, sunspots in the northern hemisphere of the sun were found to be opposite in polarity to those in the southern hemisphere. But occasional apparent exceptions indicated the need for a more careful analysis. The earliest drawings of sunspots, made by Galileo and Scheiner, suggest their complex character. They often appear at first as single spots, but soon develop into groups, frequently containing many components, large and small. No observer could fail to detect, however, a remarkable tendency of spots to occur in pairs, consisting of large spots with small companions, or of two groups of small spots. Here was an interesting chance for polarity tests, which showed that such pairs are almost invariably bipolar: that is, they consist of two spots or groups having opposite magnetic poles. The smaller spots that frequently cluster about the preceding (western) and following (eastern) major spots usually agree in polarity with the larger spots they accompany, though this is not an invariable rule.

From such characteristics a scheme of magnetic classification developed, which has been used ever since on Mount Wilson in recording the magnetic phenomena of thousands of spots examined with the 150-foot tower telescope and the 75-foot spectrograph. This long task, in which Nicholson, Ellerman, Joy and many others have taken part, has now covered more than two of the well-known sunspot cycles of approximately eleven years duration.

Law of Sunspot Polarity

It is well known that the first spots of each of these 11-year frequency cycles break out in comparatively high latitudes some time before the last of the spots of the previous cycle disappear near the equator. From 1908, the spots of the then existing cycle continued to show the same polarity, opposite in the two hemispheres, while slowly decreasing in mean latitude. Not long before the minimum of solar activity in 1912, the forerunners of the next 11-year cycle began to appear. To our surprise, their polarity was opposite to that of the spots of the preceding cycle. Moreover, the succeeding spots of the new cycle, which overlapped for a time the remnants of the old cycle in lower latitudes, retained the same reversed polarities for approximately eleven years. Then another frequency cycle commenced, with another reversal of polarity. Thus the complete magnetic cycle, bringing back spots of the same polarity as those first observed, occupies some twenty-two or twenty-three years, and comprises two frequency cycles. The northern and southern hemispheres represent this novel effect with opposite signs. The diagram shown in Fig. 1 summarises the changes of latitudes and polarities during the period 1908–35.

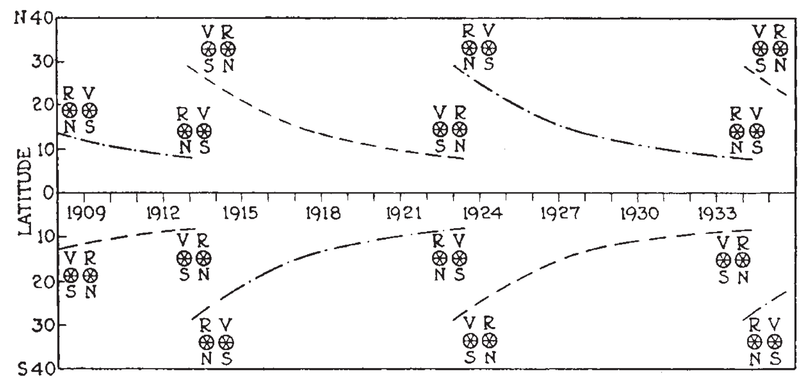

FIG. 1. Law of sunspot polarity. The curves represent the approximate variation in mean latitude and the corresponding magnetic polarities of sunspot groups observed at Mount Wilson from June 1908 until January 1935. The preceding spot is shown on the right.

A more detailed examination of the observations, many of which have been published in the *Astrophysical Journal* and the *Publications of the Astronomical Society of the Pacific*, would suffice to show that occasional exceptional phenomena complicate the explanation of these changes. About ninety-seven per cent of consistent results, however, obviously point toward some general solution, applicable to the sun and countless other stars, but still remaining in the form of the empirical law illustrated in Fig. 1.

General Magnetic Field of the Sun

Soon after the detection of strong magnetic fields in sunspots, I began to wonder whether the sun as a whole might possess a general magnetic field. There was no very promising theoretical ground for such speculation, but the magnetic field of the earth, with poles not far removed from the poles of rotation, was at least suggestive. Schuster had queried in 1891 : "Is every rotating body a magnet ?" and the structure of the solar corona resembles that of a magnetic field*. Thus while it was a far cry from the solid earth to the vaporous sun, it seemed worth while to undertake a trial.

The first attempts, made with the 60-foot tower telescope, were fruitless. In 1912, with the completion of the 150-foot tower telescope and 75-foot spectrograph, a better opportunity offered itself. Obviously no such widening and complete splitting of lines as had been found in sunspots existed in regions away from spots. But by using a purely differential method, comprising a compound quarter-wave plate overlying a long Nicol prism on the slit, it seemed barely possible that minute magnetic displacements of suitable lines might be detected by measurements on successive strips. Assuming the magnetic poles of the sun to correspond with the poles of rotation, and mounting the quarter-wave strips with their principal sections alternately at angles of $+45°$ and $-45°$ with the slit of the spectrograph, the displacements on

* In the present brief statement no attempt is made to enumerate other speculations and theories.

odd and even strips should attain maximum values on the central meridian at about 45° north and south latitude, and decrease to zero at the poles and equator.

In the search for such minute displacements, every precaution was taken to obviate any possible bias on the part of the measurers. Thus the quarter-wave plates were frequently inverted, and the measurer was never allowed to know in advance in which position they stood, nor the hemisphere or latitude of the photographs under measurement.

Great difficulties attended this investigation, which was continued for several years. Many members of the Mount Wilson staff joined me in the task, including Seares, Anderson, Ellerman and van Maanen, together with Miss Lasby, Miss Richmond and Miss Felker, while check measures and tests were made by Adams, Babcock and others. Several different types of measuring machines were employed, and every possible means of avoiding personal or instrumental errors was adopted. The results, fully described in a series of papers in the *Astrophysical Journal*, seemed to leave no room for doubt regarding the existence, polarity and approximate strength of a weak general magnetic field of the sun, having poles lying within a few degrees of the sun's poles of rotation.

The fact remains, as pointed out in these papers, that some of the many measurers engaged in the work could not detect the general field, though the results of all those who succeeded were in agreement regarding its polarity and order of magnitude. The difficulties of measurement can be appreciated only by those who have endeavoured to detect such minute displacements of lines, rendered broad and diffuse by the great dispersion employed. The observed displacements ranged from zero near the equator and poles to maximum values of 0·001 A. at mid-latitudes.

Several years ago I renewed this investigation with the cœlostat telescope (equivalent focal length 150 feet) and the 75-foot spectrograph of my solar laboratory in Pasadena. Having made a new series of photographs of the same dispersion as those previously taken on Mount Wilson, I endeavoured to measure them by several different instruments, including a Zeiss microphotometer and a tipping plate micrometer of the form used in our earlier work. The results showed little, if any, general magnetic field, and finally I thought it advisable to undertake new check measures of the plates made more than twenty years ago on Mount Wilson. More difficulties were encountered, and most of the experienced measurers who had overcome them before were no longer available. However, others kindly enlisted, and a study lasting four years has at last yielded a sufficient number of independent confirmations to satisfy us of the validity of our former conclusions.

As before, some of the measurers have been unable to detect the general magnetic field shown by our old plates. On the contrary, Dr. John Strong with an improved Zeiss microphotometer, used visually, and Dr. R. M. Langer with the original tipping plate micrometer, have found systematic average displacements of the same sign. Mr. J. Evershed, who very kindly volunteered to assist, obtained excellent confirmatory measures of our original plates at his observatory in England, using his own admirable method of measurement. Within the last few weeks [date of communication, September 14, 1935], Dr. Langer has obtained two more unmistakable confirmations with the aid of a new type of combined measuring, recording and computing machine, built in my laboratory after a design due chiefly to himself. The chief advantages of this machine are its speed of operation, permitting a very large number of measures to be made in a short time, and its complete freedom from any possibility of bias.

Taken altogether, the evidence is overwhelmingly in favour of the existence, polarity and order of magnitude of the general magnetic field of the sun given in our original papers. There is thus far no evidence of change of polarity at sunspot minima. As for any possible changes of intensity, every single determination is necessarily based upon thousands of measures, and hence represents mean values for many points on the sun. Thus much time may elapse before the question of variability can be settled.

The striking magnetic phenomena of sunspots, and the evidence we have offered that the entire sun is a magnet, would seem to have important bearings on the problems of terrestrial magnetism and the fundamental nature of magnetism itself. It is difficult to avoid the belief that the strong magnetic fields of the spots, and the much weaker general magnetic fields of the sun and the earth, arise from the same general cause, namely, the rotation of bodies carrying electrically charged particles. Many different hypotheses based upon this view have been tested, but there is much room for further work. While this will naturally deal at first with the simplest general assumptions, a detailed study of such anomalous phenomena as are presented by about three per cent of all sunspots should not be overlooked.

[1] "Sun-spots as Magnets and the Periodic Reversal of their Polarity", NATURE, **113**, 105, Jan. 19, 1924.