SOLAR VORTICES AND MAGNETIC FIELDS.

II.

I HAVE already referred to the importance of applying in astronomical research the methods of the physicist. During the last quarter of a century the study of spectroscopic phenomena in the laboratory has been completely transformed. It may well be said that this transformation, which has involved such discoveries as spectral series, the effect of pressure on wave-length, and the Zeeman effect, has been directly due to the use of Rowland's concave gratings, of great focal length, arranged for photography. In astronomical spectroscopy great advances have also been made, but the spectroscope has continued to occupy the place it formerly held as an attachment of the telescope. Although Rowland used a long-focus concave grating for his classic study of the solar spectrum, the heliostat and lens employed with this instrument gave so small a solar image on the slit that the investigation of sun-spots and other details was impossible. We thus see that while in the observatory the spectroscope continued to be used as an accessory of the telescope, in the laboratory the parts were exchanged and the telescope was employed simply as an accessory of the spectroscope. It seemed obvious that a great opportunity for advance lay open to the investigator who would combine a long-focus spectroscope with a long-focus telescope. As it would be difficult, or perhaps impossible, to use for photography a sufficiently long spectroscope attached to the tube of an equatorially mounted telescope, some form of fixed telescope was plainly essential.

The tower telescope on Mount Wilson (Fig. 5) is designed to accomplish this purpose. It consists essentially of a 12-inch refracting telescope, of 60-feet focal length, mounted in a fixed position, pointed directly at the zenith. The ordinary telescope tube is replaced in this case by a light steel tower, firmly held in position by steel guy ropes. The 12-inch objective lies horizontally at the summit of the tower, and sunlight is reflected into it from the second of two adjustable plane mirrors. The first of these mirrors is mounted as a cœlostat, and is rotated by an accurate driving-clock about a polar axis at such a rate as to counteract the apparent motion of the sun. Thus a beam of sunlight is reflected from the cœlostat mirror to the second mirror, which sends it vertically downward through the objective. In the focal plane, 60 feet below the objective, an image of the sun, about 6·6 inches in diameter, is formed on the slit of a spectrograph, at a height of about 3 feet above the surface of the ground. After passing through the slit, the light of any desired portion of the solar image (a sun-spot, for example) descends vertically into a well about 30 feet deep excavated in the earth beneath the tower. Thirty feet from the slit the diverging rays encounter a 6-inch objective, through which they pass. After being rendered parallel by the objective, the rays fall upon a Rowland plane grating, ruled with 14,438 lines to the inch. The grating breaks up the light into a series of spectra, and the rays are returned through the same objective, which brings the spectra to a focus at a point near the slit. By inclining the grating at a small angle, the image of the spectrum is made to fall at a point slightly to one side of the slit, and here the photographic plate is placed. Thus a portion of the spectrum 17 inches in length can be photographed in a single operation. In the work on sun-spots, most of the photographs are taken in the third order of the grating, where the dispersion and resolving power are very high. When the spot spectrum is being photographed, only the light from the umbra is admitted to the slit. At the end of the exposure this portion of the slit is covered, and light from the photosphere, at a point removed from the spot, is admitted to the slit on either side. Thus the narrow spot spectrum is photographed between two strips of solar spectrum, used for comparison.

The advantages of this combined form of telescope and spectrograph are considerable. On account of the great thickness (12 inches) of the mirrors, the height of the cœlostat above the heated earth, and the use of a vertical beam, the definition of the solar image is always better than with the Snow (horizontal) telescope. Another important advantage is the nearly constant temperature at the bottom of the well, where the grating is placed. This permits long exposures to be given, when necessary, without danger of such displacements of the spectral lines as would be caused by expansion or contraction of the grating. The grating used in this spectrograph is a small one, which I have employed in most of my work since 1889, but the unusual focal length of the spectrograph permits the full visual resolution of the grating to be utilised in photographic observations. Thus it has become possible to photograph the widened lines and doublets, as well as a host of narrow lines, most of them due to chemical compounds, which had not previously been recorded in the spot spectrum.

FIG. 5.—Tower Telescope on Mount Wilson.

Lack of time prevents me from discussing in this lecture the various studies of sun-spot lines carried out with this instrument before the attempt to detect a magnetic field in spots was undertaken. An extensive catalogue of these lines is nearly complete, a preliminary map has been issued and a better one is in preparation, and a series of investigations with the arc and electric furnace has suggested that the strengthening and weakening of certain lines is due to a reduction in the temperature of the spot vapours. At present we are concerned with the cause of the widening and doubling of spot lines, and the method of testing this question must now be described.

A Nicol prism was mounted above the slit of the spectrograph, and just above this a Fresnel rhomb. If the components of a spot doublet were circularly polarised in opposite directions, passage through the rhomb should give two plane polarised beams, the planes of polarisation making an angle of 90° with each other. Thus in one position of the Nicol one of the components should be photographed alone, and by turning the Nicol 90° this should disappear and the other component come into view.

When this test was applied with the tower telescope, in June, 1908, the true character of the spot doublets became apparent (Fig. 6). One or the other component of the

[1] Discourse delivered at the Royal Institution on Friday, May 14, by Prof. George E. Hale, For.Mem.R.S. Continued from p. 23.

doublet could be cut off at will by rotating the Nicol, precisely as Zeeman had done in the laboratory. On account of the unique character of the Zeeman doublets, this test alone was almost sufficient to prove the existence of a magnetic field in sun-spots. But one of the great beauties of the Zeeman effect is its many-sided character, which permitted the test to be multiplied and extended. From Zeeman's first experiments it was known, for example, that if the strength of the magnetic field is insufficient to separate completely the components of a doublet, the edges of the resulting widened line should be circularly polarised in opposite directions. Thus those lines which are widened, but not doubled, in spots might be expected to shift in position when the Nicol is rotated. This was found to be the case. Again, the lines which constitute the flutings of the spectra of compounds are not, in general, affected by a magnetic field. Hence such lines in the spectrum of a sun-spot should not be shifted when the Nicol is rotated. This, also, was found to be true. But a still more satisfactory test was suggested by another laboratory phenomenon. When a doublet is observed along the lines of force, with one of the components extinguished by the Nicol, reversal of the current through the magnet should extinguish the visible component and cause the invisible one to appear. In the sun, according to our hypothesis, reversal of the direction of revolution in a vortex should correspond to reversal of the current through the coils of a magnet. Hence the red component of a doublet should appear in the spectrum of a vortex rotating in one direction, the violet component in that of a vortex rotating in the reverse direction. Fortunately, the appearance, on opposite sides of the solar equator, of two spot vortices rotating in opposite directions (Fig. 4) made this test possible. The results were perfectly in accord with the hypothesis.

So far we have been considering only such phenomena as are observed parallel to the lines of force of a magnetic field; but a spectral line which, in such circumstances, appears as a doublet is usually transformed into a triplet when the observation is made at right angles to the lines of force. The circularly polarised side components of the doublet give place to plane polarised components, occupying the same position, while another line appears centrally between them. The light of this line is also plane polarised, the direction of the vibrations being parallel to the field, while the vibrations of the side components are in a plane at right angles to the field. Thus when a spot is carried by the solar rotation to a point near the limb we might expect the double lines in its spectrum to be transformed into triplets if produced by a magnetic field. The failure of the central line to appear seemed to raise an important argument against the magnetic hypothesis.

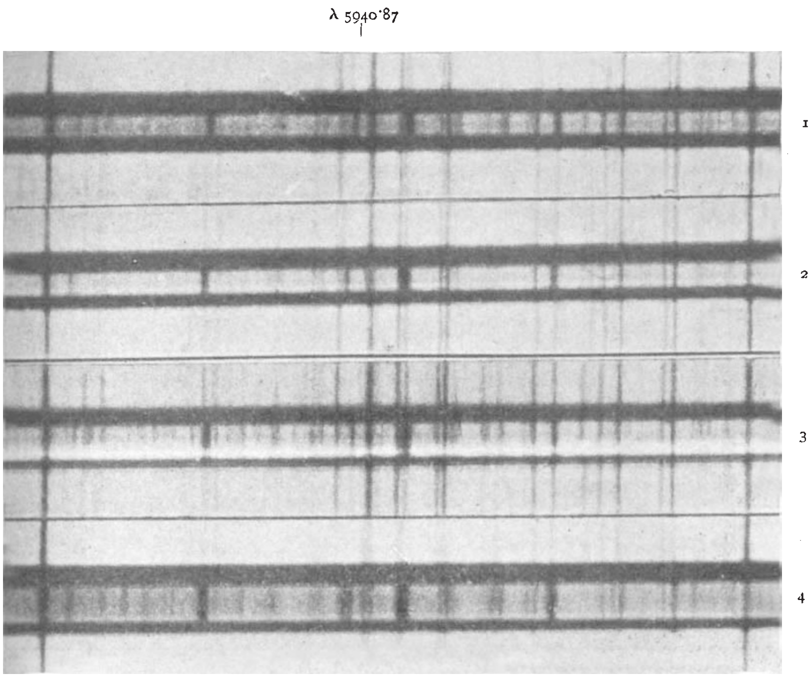

FIG. 6.—(1) Southern Spot, showing Red Components of Doublets. Nicol, 29° W. (2) Northern Spot, showing Violet Components of Doublets. Nicol, 29° W. (3) Northern Spot, showing Red Components of Doublets. Nicol, 61° E. (4) Spot Spectrum without Rhomb or Nicol, showing both Components of Doublets.

At this point the necessity of conducting laboratory investigations in immediate conjunction with astronomical observations is well illustrated. Fortunately, our laboratory was already well equipped for work of this nature (Fig. 7). In anticipation of the possibility that observations of the Zeeman effect would be needed in the interpretation of solar and stellar phenomena, a powerful electromagnet, with suitable accessory apparatus, had been provided. A brilliant spark, produced between metallic electrodes in the field of the magnet, furnished the source of light. As many of the double lines in sun-spot spectra are due to iron, this metal was selected for the first experiments. The spectrum was photographed, at various angles with the lines of force, with a powerful spectrograph, like the one used with the tower telescope, similarly mounted in an underground chamber.

The difficulty of accounting for the behaviour of the iron doublets in the sun was removed by these investigations. It appears that these lines do not become triplets when observed across the lines of force. In reality they are changed to quadruplets, or doublets in which each of the components is a close double line. In the magnetic field of sun-spots, which is much weaker than the field used in the laboratory, the closely adjoining lines which constitute the components of the doublets cannot be separated. Thus these sun-spot lines should appear double at whatever position the spot may occupy on the sun's surface.

The distance between the components of doublets or triplets separated in the magnetic field varies greatly for different lines. Some exceptional lines are not affected in the least, others are merely widened, and others are clearly and sometimes greatly separated. It is therefore important to compare the widening and the separation of lines in a sun-spot spectrum with the corresponding phenomena in the magnetic field. With few exceptions, most of which may be accounted for by the presence in the spot spectrum of closely adjoining lines of other elements, the solar and laboratory results were found to be in good agreement. The following table gives a comparison of certain iron lines in the spot and laboratory:—

Wave-length	Δλ, spark	$\frac{\Delta\lambda\text{, spark}}{5\cdot1}$	Δλ, spot	
6213·14	0·703	0·138	0·136	−0·002
6301·72	0·737	0·144	0·138	−0·006
6302·71	1·230	0·241	0·252	+0·011
6337·05	0·895	0·175	0·172	−0·003

The column headed "Δλ, Spark" gives the distance between the components of the lines as observed in the laboratory. As the strength of the magnetic field used in the laboratory was about 5·1 times that of the spot, the quantities obtained by dividing the separations in the second column by 5·1 are given in the third column. These separations are directly comparable with the separations of the corresponding lines in the spot, which are given in the fourth column. The fifth column shows that the differences between the solar and laboratory results are very small. As the strength of the field in the laboratory was about 15,000 gausses, the strength of the field in this spot would be about 15,000÷5·1=2900 gausses. The strongest field hitherto measured on our photographs of spot spectra is about 4500 gausses, corresponding to a considerably greater separation of the lines (Fig. 8).

When a similar comparison was made for various lines of titanium and chromium, a much less perfect agreement between the spot and laboratory results was found. It had already been observed that such lines as D of sodium and *b* of magnesium, which undoubtedly represent a much higher level than the great majority of lines in the spot spectrum, are but very slightly widened. As these lines are strongly affected by a magnetic field in the laboratory, it appeared evident that the strength of the field in spots must fall off rapidly in passing outward through the spot line crowds the components so closely together that they are not readily separated with the resolving power available. As these triplets are photographed even when the spot is very near the middle of the sun, it is evident that the spot always sends out light which makes a considerable angle with the lines of force. In a normal triplet the central line is of twice the intensity of the side components, when observed at right angles to the lines of force, and disappears altogether when observed parallel to the lines of force. Thus, by determining the relative intensities of the central and side lines of such a triplet, the angle between the lines of force and the line of vision can be obtained. In the case of sun-spots, the data at present available are not sufficient for the accurate determination of this angle, but it seems to lie between 30° and 60° when the spot is near the centre of the sun. On the hypothesis that the magnetic field is produced by the spot vortex, it would then follow that the axis of the vortex, instead of being radial, as we at first assumed, makes an angle of much less than 90° with the surface of the photosphere.

The time at my disposal permits me to describe briefly only a few other phases of this investigation. In the laboratory the central line of triplets is polarised in a

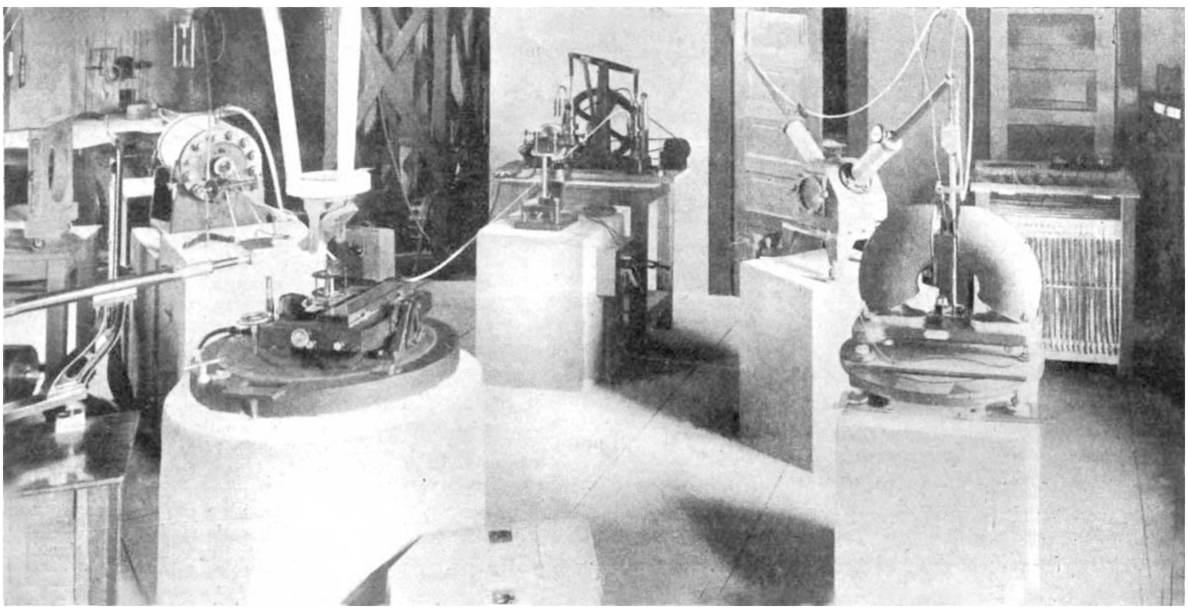

FIG. 7.—Interior of Pasadena Laboratory, showing Slit-end of Vertical Spectrograph and Magnet used in study of Zeeman effect.

vapours. In these circumstances lines of other elements, which represent levels higher than the average, should show small separations in the magnetic field of the spot. It seems probable that in this way the lack of perfect agreement between the laboratory and solar results observed in the case of titanium and chromium can be accounted for.

A further important test was afforded by the well-known phenomenon exemplified in Preston's law. According to this law, the distance between the components of the lines split up by a magnetic field varies directly as the square of the wave-length. This we found to be true even in the case of a metal like iron, the lines of which cannot be grouped into series, if the average separations of a sufficient number of lines were considered. We should therefore expect that the widening of lines in spots would rapidly decrease toward the violet, and that the separation of spot doublets should diminish in a similar way. A study of the spot spectrum shows that this actually occurs.

It soon appeared that the normal spot spectrum always contains triplets as well as doublets (Fig. 8). These are less easily recognised, because the presence of the central plane parallel to the magnetic field. Hence, if the light is passed through a Nicol prism, used without a rhomb, it should be possible to extinguish this line at certain positions of the Nicol, in which case a spot triplet would appear as a doublet. This test has also been applied to the spot triplets, with the expected result. In fact, this method supplies a convenient means of recognising close triplets, the components of which are too closely crowded to be seen separately before the central line is cut out. Indications have also been obtained of what may prove to be unequal rotation of the plane of polarisation of this central line in different parts of spots. The gradual decrease in the strength of the field from the umbra to the outer limit of the penumbra has been studied, and magnetic fields have been detected on the sun's disc, in certain regions outside of sun-spots. It is evident that many new phases of the subject are likely to be developed in the future, especially if larger images of the sun and more powerful spectrographs are employed. In this connection it may be stated that a tower telescope of 150-feet focal length, to be used on Mount Wilson with a spectrograph of 75-feet focal length, is now under construction.

This will give a focal image of the sun about 16 inches in diameter, in which small spots, as well as large ones, can be studied.

Although it now seems to be demonstrated that sun-spots are electric vortices, judgment should be reserved as to the various theories which have been advanced to account for their origin. Many of the results I have described appear favourable to Emden's solar theory, but it seems to be opposed by the important investigations of Evershed, who has found that the metallic vapours in sun-spots flow radially outward from the umbra, parallel to the photosphere. The further development of Evershed's work, and the continued study of solar vortices and magnetic fields, should soon permit a trustworthy theory of sun-spots to be formulated.

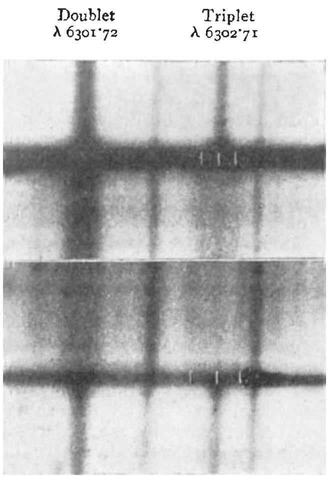

FIG. 8.—Iron Doublet (λ 6301·72) and Triplet (λ 6302·71) in Two Spot Spectra, showing Field Strengths of 2900 and 4500 Gausses respectively.

It is evident that the rapid decrease upward of the strength of the field in spots would prevent this field from having an appreciable influence on the higher solar atmosphere. At the distance of the earth, as Schuster has shown, the combined magnetic effect of several spots, all assumed to be of the same polarity, and having no such rapid decrease in field strength at higher levels as is actually observed, would be altogether incompetent to account for terrestrial magnetic storms.

In concluding, I wish to express my appreciation of the assistance I have received from my colleagues at Mount Wilson. I am particularly indebted to Messrs. Adams, Ellerman, King, Nichols, and St. John for aid in connection with the present investigation.

THE NEW ROOMS OF THE ROYAL SOCIETY OF EDINBURGH.

ON Monday, November 8, the new rooms of the Royal Society of Edinburgh were formally opened by an appropriate inaugural address from the president, Sir William Turner, followed by a brilliant reception. For the purposes of the reception the ordinary meeting-room was transformed into the cloak-room, and the president's address was delivered in the Freemasons' Hall, a few blocks further west in George Street. After the address the audience re-assembled in the society's new abode, and had every opportunity of inspecting the arrangements which had been made for the accommodation of the large and growing library and for other possessions of the society.

The important events which led up to the migration of the society from its historic haunts in the beautiful building in Princes Street were described by the president in his address. The National Galleries of Scotland Bill, introduced into the House of Commons in 1906, provided that the Royal Institution, so long the home of the society, should form a part of the National Gallery of Scotland and be applied to the promotion of the Fine Arts. As the result of representations made by the society, a clause was introduced into the Bill by which the Treasury was empowered to provide funds both for the purchase and equipment of a new habitation for the society, and for an annual grant of 600*l.* to assist in the discharge of the scientific work. The natural feeling of regret at having had to give up one of the finest sites to be found in any city of the world is partly balanced by the knowledge that now the society has, for the first time in forty or fifty years, ample accommodation for its valuable library.

When the building now occupied by the society was vacated two years ago by the Edinburgh Life Assurance Company, operations were at once begun by the Board of Works to fit it for its new function. No structural changes of magnitude were needed to make the rooms effective for their purpose. The late librarian, Mr. Hardy, whose lamented death last spring deprived the society of a singularly efficient and devoted officer, had meanwhile been planning the whole arrangements of the library, and what is now seen is largely the result of his forethought and attention to details.

The building is entered by two doors. The east door is open daily, and through it entrance is at once gained to the front saloon, where there is every convenience for reading and writing. The west door is opened only on meeting days. It leads directly into a staircase, by which immediate ingress is gained to the meeting-room, which is fitted with a lecture table and appliances of various kinds. By the same staircase, also, access is had to the reception room on the first floor and to various library rooms on the second floor.

The guests on the night of the reception passed up the west staircase, at the first turn of which a fine bust of Cuvier greeted them with calm dignity.

Along the walls of the meeting-room (transformed for the occasion into the cloak-room) some other interesting busts are to be seen—Berzelius, John Playfair, Rev. Sir H. Moncrieff Wellwood, and Sir Walter Scott; also an engraving of the statue of Sir Joseph Banks in the British Museum, executed by Chantrey. A photograph of Sir Richard Griffith and an engraving of D. Milne Horne also decorate the walls.

Passing out of the meeting-room and up a few steps we come to the ante-room, with oil portraits of James Watt and William Murdock, one of the pioneers of gas lighting. In the handsome reception-room immediately adjoining are portraits of former well-known presidents and secretaries—Sir T. Makdougall Brisbane, Sir James Hall, Profs. J. D. Forbes and John Robison, the last a Raeburn; also a bust of Sir Roderick Murchison occupies one corner. Passing across the reception-room we emerge at the head of the east staircase, which leads down to the front saloon and to the east door. The portraits which decorate the walls of this fine staircase are (beginning from the top) those of Piazzi Smyth, Patrick Neill, Sir David Brewster, Sir Robert Christison, Sir Walter Scott, and the first president, Henry, Duke of Buccleuch. In addition to these there are several good engravings of portraits of Henry Mackenzie (the "Man of Feeling"), the Right Hon. Jas. Moncrieff, and Dr. William Robertson, the historian (a fine engraving by J. Dixon from the portrait by Sir Joshua Reynolds).

The front saloon has its walls covered with books, and contains a life-like bust of James Gordon, the late librarian. Opening off it at the north-west corner is the librarian's room or office, with a portrait of Sir Humphry Davy over the mantelpiece. Adjoining it is the council-room, with the well-known portrait of Prof. Tait (by Sir George Reid) hanging above the fireplace, and on each side a drawing of the birthplace of Sir Isaac Newton, presented to the society by a son of Prof. Robison. The same donor also gave a small carved door, which formed part of a book-press belonging to Newton. Passing out of the council-room by a door in front of the foot of the east staircase, and turning along a passage to the right, we come to a large oblong room called the back saloon. Round the walls are steel book-cases filled with the Transactions and Proceedings of various scientific societies of foreign countries. The countries are arranged alphabetically, and under each country the towns are similarly arranged, so that a visitor has not the least difficulty in finding the shelves on which the publications of any given society are placed.

Near the council-room door a staircase leads down to the basement, where, in addition to rooms set apart for shelving books, are strong-rooms for storing the society's own Transactions and Proceedings, and the blocks and plates of illustrations. These are all admirably arranged, so that the stock in hand can be estimated almost at a glance.

Taking a general survey of the contents of the many book-cases which line the walls of the various rooms, we soon recognise the guiding principle of the whole. The