Supplement to NATURE

No. 2957

JULY 3, 1926

Some New Possibilities in Solar Research.

By Dr. GEORGE E. HALE, For. Mem. R.S.

FORTY years ago I began a series of visual and photographic studies of the sun. Recently I have returned to this work, after an interval of enforced absence. My instrumental equipment is now augmented by the addition of a spectrohelioscope, a simple device for monochromatic vision which we owe in its essence to the pioneers of solar research. This renders visible a host of important phenomena hitherto concealed from view by the overpowering brilliancy of the sun's disc. Chief among these are the radiating and absorbing regions of the hydrogen atmosphere, visible with the spectroscope in profile at the sun's limb, and revealed in projection by spectroheliograms of the disc, but now accessible, wherever they may be situated, to visual observation with instruments of moderate size.

All readers of NATURE who are familiar with its early volumes will remember the discoveries of Janssen and Lockyer in 1868. At the total solar eclipse of that year, Janssen, who was observing in India, was so impressed by the brilliancy of the lines in the spectrum of the prominences that he determined to look for them in full sunlight. He did so, and was at once rewarded. The bright light of the sky around the sun, which ordinarily hides the prominences from us, gives the spectrum of scattered sunlight. Entering the spectroscope through a slit from one to three-thousandths of an inch wide, it is spread out into a band from a few inches to forty feet in length, depending upon the dispersive power of the spectroscope. Its intensity may thus be reduced indefinitely. The bright lines of the gaseous prominences, however, are essentially monochromatic. High dispersion separates them more and more widely, without greatly weakening them. They thus become readily visible on a fainter background of dispersed skylight. The principle involved was first stated by Lockyer in 1866 and successfully tested by him in 1868, before the news of Janssen's discovery had reached Europe. This application of the spectroscope opened a new and productive era in solar physics, enlisting the active efforts of astronomers in England, France, Italy, Germany, and the United States.

Naturally these observers wished to see not merely the spectra of the prominences, but also their forms. In his well-known book, "Contributions to Solar

Physics" (p. 578), Lockyer describes how the first steps were taken:

"In my first paper I gave some drawings procured by causing the slit to pass slowly over the prominence. By this means a number of sections of varying length was obtained, which, placed side by side, gave an idea of its shape. The slit then used was extremely narrow, and was radial to the sun's limb. It was obvious that in this way the true shape of the prominence could not be seen unless the slit were moved with sufficient rapidity to allow of persistent images. At the very outset Janssen and myself attempted to accomplish this, Janssen by giving a rotatory motion to a direct vision spectroscope, I by giving an oscillating motion to the slit, in which I was followed by Young, who afterwards expanded it."

Prof. Young's account of his instrument is as follows:

"The eye-piece of the instrument has an apparatus attached, which, however, thanks to the high dispersive power, I find unnecessary.

"It was early proposed by Janssen to use a vibrating or rotating slit in order to make visible the form of a solar prominence, but as Zöllner has shown, the mere opening of the slit answers just as well, the light of the protuberance being diluted to precisely the same extent in either case.

"It occurred to me in connexion with a suggestion of Professor Morton, that by interposing at the focus of the eye-piece a diaphragm which should move with the vibrating slit, the light of the neighbouring portions of the spectrum might be cut off and this dilution avoided. Mr. Clark has devised and constructed a very beautiful mechanical arrangement by which this simultaneous and accordant motion of slit and diaphragm is effected by the rotation of the small fly-wheel shown in Fig. 1.

"But I find, that although seen in this way, the prominences appear very bright; yet the working of the apparatus always causes a slight oscillation of the equatorial, which interferes with the definition of details, and I prefer to work with the slit simply opened." (Young, NATURE, Dec. 8, 1870.)

The introduction by Zöllner and Huggins of the wide slit method and the superb views it afforded of the prominences at the limb led to its universal adoption, and the oscillating slit was abandoned. Although Lockyer and Young often examined the spectra of sun-spots and other regions of the photosphere, and repeatedly described reversals and distortions of hydrogen

and other lines, I can find no indication that the oscillating slit device was ever tested for the observation of the forms of eruptions or other phenomena on the disc. Nevertheless, the credit for building the first spectro-

with a simple spectroheliograph at the Kenwood Observatory in the spring of 1891. In January 1892, with an improved spectroheliograph, I succeeded in photographing the chromosphere and prominences (Fig.

FIG. 1.—Active prominence, 140,000 miles high, photographed by Ellerman at Mount Wilson, July 9, 1917, with the K line of calcium. The small disc represents the comparative size of the earth.

helioscope (as I have named the instrument) and applying it to the observation of prominences at the limb belongs to my old friend Prof. Young, who was also the first to take photographs of the forms of the prominences through an open slit (*loc. cit.*).

THE SPECTROHELIOGRAPH.

The principle of the spectroheliograph, which does not differ greatly from that of Young's instrument with oscillating slit, occurred to me in 1889.¹ It involves the use of a spectroscope with a fixed second slit, through which a single line is admitted to a photographic plate. The whole spectroscope is mounted on steel balls, and moved slowly by a motor across the solar image, which, like the photographic plate, remains stationary. Or the spectroscope may be fixed in position, and the solar image and plate moved at the same speed across the first and second slits respectively. A monochromatic image of the sun is thus gradually built up on the plate from countless successive images of the narrow second slit.

After some preliminary experiments at the Harvard Observatory, I obtained photographs of prominences

¹ I afterwards found that it had been first suggested by Janssen, embodied in a practicable design by Braun (not constructed), and unsuccessfully tested by Lohse.

1) surrounding the sun and the bright flocculi² revealed on the disc by the use of the H or K line of calcium.

About this time Deslandres introduced the velocity spectrograph for photographing the H or K line in successive sections of the sun. Evershed soon constructed and systematically employed a spectroheliograph, and in 1893 Deslandres also began work with a spectroheliograph, which he employed for photography with the calcium lines and with some of the narrower dark lines. In 1903, with the Rumford spectroheliograph attached to the 40-inch refractor of the Yerkes Observatory, Ellerman and I first photographed the bright and dark hydrogen flocculi on the disc and noted especially the long dark flocculi (Fig. 2) identified as prominences projected against the sun (named 'filaments' by Deslandres, who has studied them extensively at Meudon with the spectroheliograph and velocity spectrograph). Five years later, at Mount Wilson, aided by plates sensitised for photography in the red, Ellerman and I discovered large vortices

FIG. 2.—Hydrogen ($H\alpha$) flocculi, photographed with the 13-foot spectroheliograph at Mount Wilson, February 17, 1926, at 10^h 00^m. All of these could be seen in Pasadena with the spectrohelioscope.

surrounding sunspots (Figs. 3 and 10). The $H\alpha$ line, with which the vortices were found, is much more

² Flocculi is a general term applying to all markings, bright or dark (excepting sunspots), photographed by the spectroheliograph on the sun's disc.

effective than the more refrangible hydrogen lines for the study of the hydrogen atmosphere of the sun. Its situation in the red also adapts it for visual observations, particularly at low altitude stations where smoke and haze may seriously interfere with work at the violet end of the spectrum. With a spectroheliograph of high dispersive power, $H\alpha$ shows also the 'alignments' discovered by Deslandres, which constitute a reticular structure of wide mesh associated with the filaments.

The spectroheliograph, in addition to providing a method of photographing the chromosphere and prominences at the sun's limb, has thus made possible the daily study of the solar atmosphere in projection against the disc. But useful as it has proved, the need for a similar means of visual observation has persisted for many years.

THE SPECTROHELIOSCOPE.

My first attempts to observe the hydrogen flocculi visually were made on Mount Wilson with the 60-foot tower telescope and 30-foot spectroheliograph soon

bearing standing midway between them. Each of these radial slits, when near the axis of the collimator, thus produced a spectrum, and by adjusting the grating (or prism) the $H\alpha$ line could be brought into coinci-

FIG. 3.—Hydrogen ($H\alpha$) vortices surrounding the bipolar sunspot of September 1924, photographed by Lewis Humason at Mount Wilson with the 13-foot spectroheliograph.

FIG. 4.—Solar Laboratory in Pasadena. The second mirror of a cœlostast beneath the dome sends parallel rays vertically downward to a 12-inch objective, giving a 2-inch solar image on the slit of the spectrohelioscope in the basement. By a simple change, a Cassegrain reflector of 18 inches aperture, giving a solar image either $6\frac{1}{2}$ inches or $16\frac{1}{2}$ inches in diameter, can be substituted for this objective.

after the discovery of the $H\alpha$ vortices in 1908. A disc carrying a large number of radial slits was mounted just above the wide first and second slits on a vertical

dence with the corresponding slit on the opposite end of the same diameter. A given displacement of the first slit produced an equal displacement of the $H\alpha$ line in the opposite direction. Thus, when the disc was rotating, the observer, looking through a positive eye-piece focussed on the slits coinciding with the $H\alpha$ line, saw an image of a portion of the sun in hydrogen light. Unfortunately, the slits were too wide and too few in number, and for many years I had no opportunity to bring the method into effective form.

In 1923 I renewed the effort, with results which have been described in these pages (*NATURE*, October 25, 1924, p. 628). At that time, however, the apparatus was crudely mounted, and its consequent inefficiency, at a period of low solar activity, gave me no measure of its actual powers. Recently the same optical parts, now adequately mounted in my new Solar Laboratory in Pasadena (a branch of the Mount Wilson Observatory), have yielded results of greater interest.

A very brief description of the instrument will suffice. Imagine a reflecting spectroscope of 6 inches aperture and 13 feet focal length, standing vertically in a well beneath the laboratory (Fig. 5). A solar image 2 inches in diameter is formed on the slit by a 12-inch objective.

A cœlostæt, with second mirror, mounted beneath a dome at the summit of a low tower (Fig. 4) sends parallel rays of sunlight vertically downward to the 12-inch objective, which stands 18 feet (its focal length) above the slit. Electric slow motions, controlled by buttons within easy reach of the observer, permit the objective to be focussed and the solar image to be moved in any direction across the slit. Thus all parts of the limb or disc can be examined in quick succession.

are such that the second slit constantly bisects the oscillating *H α* line, a monochromatic window, one-quarter of an inch wide, is thus provided through which to view the sun. A positive eye-piece magnifying about 2.5 diameters, mounted on the binocular body of my Spencer microscope, is used for observing the hydrogen atmosphere through this window. The speed of the driving motor is fast enough to give a persistent image. As the (visible) length of the window thus employed is

FIG. 5.—Upper end of combined spectroheliograph, spectrograph, and spectrohelioscope, mounted vertically in a well 10 feet in diameter and about 80 feet deep. The oscillating slit-bar and binocular eye-piece may be seen near the middle of the instrument. These are ordinarily employed with a reflecting spectroscope of 13 feet focal length, also designed for use as a spectrohelioscope. By turning its optical parts out of the way, the instrument is transformed into a Littrow spectrograph of 75 feet focal length, suitable for researches on the magnetic fields in sunspots.

The second slit lies in the plane of the spectrum, formed by a large plane grating, ruled by Jacomini on the ruling machine of the Mount Wilson Observatory. The first order spectrum, which is very bright, is usually employed. The *H α* line is brought into coincidence with the second slit, which is narrower than the (dark) line. The slits are carried at opposite ends of a horizontal bar, which can be oscillated (usually through a range of a quarter of an inch) about a bearing half-way between them (Fig. 6). As the optical arrangements

about half an inch, a considerable portion of the 2-inch solar image can be seen at once.

I was agreeably surprised when I first tried this apparatus on January 16 of the present year. I knew from previous experience that the prominences at the limb and the more conspicuous dark and bright flocculi on the disc would be visible, but I was scarcely prepared for the delicate details of structure, both dark and bright, which appeared in good contrast on the disc. At that time (as in the earlier work) I was using five

slits at each end of the bar, instead of one. These were only one-twelfth of an inch apart, restricting the field of view to this width. The central image in the eyepiece, corresponding to the $H\alpha$ line, was flanked on either side by brighter images of the same region,

prominence, from a spectroheliogram taken some years ago by Ellerman on Mount Wilson, is illustrated in Fig. 7. It will presently appear why objects of this nature can often be better seen with the spectrohelioscope than they can be photographed with the spectroheliograph.

FIG. 6.—Plan of spectrohelioscope. The oscillating slit-bar, mounted on a bearing movable by the micrometer screw near the centre of the photograph, is driven by a motor at the left (shown in Fig. 5). The observer looks through the binocular eye-piece, which is focussed on the second slit. The 18-inch concave mirror of the Cassegrain reflector, the driving mechanism and sliding plate-holders of the spectroheliographs, and the buttons for electric control, may also be seen in the photographs.

formed by the light of the continuous spectrum. Thus, in examining a spot region the hydrogen flocculi above and about the spots could be seen in the central image while the underlying spots and photosphere appeared in the side images—a convenient means of comparison. Frequently in the hydrogen image the spots are entirely concealed by flocculi, and in tracing the spiral structure in a vortex to its objective, it is advantageous to be able to see the spots simultaneously. For this and other reasons two or more second slits may sometimes be preferred to one. By means of a special device, however, similar comparisons can be easily made with only one second slit.

set on different parts of the $H\alpha$ line is a vital factor here.

EFFECTS OF LEVEL AND OF RADIAL MOTION.

In our early work with the spectroheliograph, M.

FIG. 7.—Solar prominence partly projected upon the disc, photographed by Ellerman at Mount Wilson with the 13-foot spectroheliograph (using $H\alpha$) May 22, 1916. At the left is a longer exposure of the same prominence, made with the disc covered.

EXPLORING THE SOLAR ATMOSPHERE.

As a quick and effective means of exploring the entire solar atmosphere the spectrohelioscope is unrivalled. In a few minutes one may run completely around the limb, not only observing the chromosphere and prominences projecting beyond it, but also following with equal ease those which extend on to the disc and appear there as dark absorbing masses. Such a

Deslandres and I independently utilised the principle of photographing cross-sections of the calcium flocculi at different levels by setting the second slit in successive exposures at various distances from the centres of the H and K lines. As these lines widen in descending through the calcium atmosphere toward the photosphere, it is obvious that if the second slit is set at a given distance from the centre, none of the higher

calcium vapour, which gives a narrower line, can be included in the photograph. Similar work was afterwards undertaken with the hydrogen lines, where the

second slit compatible with good definition and contrast.³ But the discriminating power of high dispersion is very advantageous in many cases, and a means of utilising it without the limitations incident to the simultaneous use of only two second slits, or the delays involved in making a series of exposures like that in Fig. 8, is clearly desirable, especially in the case of rapidly changing eruptions. This is afforded by the spectroheliograph, because of the ease of quickly shifting the position of the *H α* line on the second slit while observations are in progress. Of the various devices I have employed for this purpose, perhaps the simplest is a piece of plane, parallel glass, mounted on trunnions just below the oscillating second slit. When this glass plate is tipped up or down, the line is displaced to red

FIG. 8.—Five exposures by Ellerman with the 13-foot spectroheliograph, showing the changes in the flocculi corresponding to second-slit position, ranging from $\lambda 6564.36$ (left) to the centre of *H α* (May 29, 1916).

velocity of the gas in the line of sight is often of greater significance than its level.

Fig. 8 illustrates the different appearances of a given region of the solar atmosphere when photographed with the second slit at various distances from the centre of *H α* . Many studies of this kind have been made at Mount Wilson, and these have been supplemented by other investigations based upon photographs taken with a single first slit, an optical system giving two spectra of the same region of the sun, and two second slits, one set on the red side of *H α* in one spectrum, the other on its violet side in the second spectrum, equidistant from the centre of the line. Two photographs of the same region of the hydrogen atmosphere thus obtained simultaneously often show remarkable differences, as Fig. 9 illustrates. In this picture of an active spot region the bright eruptive flocculi appear in both photographs, because the corresponding bright *H α* line was wide enough to overlap both of the second slits. The dark flocculi, produced by the cooler gas at a much higher level, gave a narrower line, displaced to the red because of the rapid descent of this gas. The structure of this rapidly falling gas is consequently shown only in the lower photograph, made with the second slit set on the red side of the line.

The power of the spectroheliograph thus to single out gaseous masses moving rapidly in the line of sight is one of its most valuable properties. This effect can be minimised, if it is desired to record on a single plate all bright and dark flocculi moving at moderate radial velocities, by using the lowest dispersion and widest

or violet. A scale in the eye-piece shows the exact position of the line on the slit. This is readily converted into a 'blink' apparatus for comparing the images of the flocculi corresponding to the red and violet edges of the line. An electromagnet for tipping the plate and two adjustable stops to define its limits serve for this purpose.

With a device of this kind, or with a micrometer screw which permits the oscillating bar (and thus the second slit) to be displaced toward red or violet (shown near the centre of Fig. 6), it is fascinating to watch the changes in the appearance of the flocculi, and to distinguish between ascending and descending gases. In fact, we have here a special means of analysing the

H α line and of separating the complex elements of which it is composed. Areas in the solar atmosphere which give rise, for example, to bright *H α* lines dis-

FIG. 9.—Two photographs of the hydrogen flocculi associated with an active sunspot group, made simultaneously with light from the violet (upper) and red (lower) sides of the *H α* line. The bright eruptive regions are similar in the two cases, while the lower photograph shows also the dark flocculi caused by the absorbing gas at higher levels, descending toward the photosphere.

³ Or (if higher dispersion is employed) the *H α* line may be caused automatically to move back and forth across the narrow second slit during the exposure.

placed toward the red frequently lie in the line of sight or in such close proximity that they cannot be distinguished in photographs of the $H\alpha$ line in the spectrum of the region. Thus in measuring the displacement of this line near spot groups or in other parts of the sun's disc we are dealing with an integrated effect, representing the superposition of the various $H\alpha$ lines given by the superposed or closely contiguous areas in question. With the spectrohelioscope many of these areas can be separately distinguished and their radial velocities determined by moving the line back and forth over the second slit and noting the displacement from its centre, towards red or violet, when a given bright or dark structure reaches its maximum of intensity. Furthermore, the width of the bright or dark $H\alpha$ line corresponding to any detail of structure can also be measured by taking the scale readings, to red and violet, at which this structure disappears. Indeed, it would not be difficult, by a simple photometric device, to determine the exact intensity curve of the line given by any of the small flocculi.

I am referring to observations within the boundaries of the dark $H\alpha$ line and its two wings (each of which is about as wide as the dark line itself), and not to the large local displacements which are often seen in or near active spot groups. It should be added, however, that the spectrohelioscope is also well adapted for the observation of the rapidly moving gases which give rise to these large displacements. The form of the gas moving at any given velocity can be seen by setting the oscillating slit at the corresponding distance from the centre of the line.

PROMINENCES, FILAMENTS, VORTICES, AND ERUPTIONS.

Even for the observation of prominences projecting outside the limb, the oscillating slit has some advantages over the wide slit. This is because the former shows them in essentially monochromatic light, and thus often permits details to be seen which are confused with a wide slit because of the superposition of gaseous masses moving at different velocities in the line of sight. By setting the oscillating slit on different parts of the line, portions of the prominence moving at different velocities can be seen separately, as in the case of the flocculi just cited. Prominences in which there are marked internal differences of radial velocity sometimes

do not appear at all on the disc at the slit position which shows them best outside the limb. A turn of the micrometer screw, however, suffices to reveal them in strong contrast, either as filaments or in other forms.

This suggests the use of a spectrohelioscope as a guiding device for a spectroheliograph, permitting the $H\alpha$ line to be frequently readjusted on the second slit of the latter instrument during exposures, so as to record all phenomena at the limb and on the disc in strongest contrast. The spectrohelioscope itself may also be used for photography, either in the form described here, provided with an auxiliary camera and right-angle prism for visual observations between exposures on small areas; or as a spectroheliograph with

Fig. 10.—Hydrogen ($H\alpha$) vortex photographed by Benioff at Mount Wilson with the 13-foot spectroheliograph. Simple vortices of this character are selected for determining the law of storms in the solar atmosphere.

oscillating slits, capable of photographing the entire solar disc. With the former arrangement, the changes in the appearance of given areas when $H\alpha$ is moved across the second slit may be recorded, perhaps even in the form of moving pictures.

I cannot dwell, however, on the remarkable phenomena thus brought to view. Some of them are illustrated in Figs. 2 and 11, but these spectroheliograms are quite inadequate to show the delicate details,⁴ and they of course fail to indicate the effect of shifting the line on the slit. Brief reference should be made, however, to observations of vortices and eruptions.

I have previously described in NATURE our researches

⁴ This remark refers to our spectroheliograms with 2-inch solar image. The details of the vortex structure are best shown by our spectroheliograms of the 6½-inch solar image given by the 60-foot tower telescope on Mount Wilson (see Figs. 3 and 10). I am not yet certain whether the most delicate details on such photographs can be so well seen with the spectrohelioscope.

at Mount Wilson on the law of sunspot polarity.⁵ This is part of a more general investigation on the law of whirling storms in the sun, which we find to be much more complicated than the terrestrial law. The bipolar vortices which constitute typical sunspots are of opposite polarity in the northern and southern hemispheres of the sun, and these polarities are reversed at each sunspot minimum. The available evidence favours the view that this magnetic change is due to a reversal in the direction of whirl in the vortices that

helioscope a very useful means of continuing the investigation. If, as often happens, a prominence (or filament) occurs as a dark flocculus near a spot, its spiral form may at once indicate the direction of whirl in the vortex. Owing to differences in radial velocity, a slight change in the position of the $H\alpha$ line on the oscillating slit is frequently necessary to show such a vortex clearly. For detailed studies of vortex structure and changes of form, both in plan on the disc and in cross-section at or near the limb, the spectrohelioscope has also shown its efficiency.

This instrument is also of great service for the detection of such violent outbursts on the sun as I observed on January 24 (Fig. 11) and 25, 1926, preceding the great aurora and magnetic storm of January 26 and 27 already described in NATURE (February 6, p. 208). The eruption, which continued for several hours on January 25, surpassed in brilliancy all solar phenomena I have ever before seen, and exhibited rapid changes of form.⁷ Because of the ease of glancing occasionally during the day at probable regions of activity, and

FIG. 11.—Bright eruption in great sunspot group at 22° N. latitude, photographed at Mount Wilson with the 13-foot spectroheliograph, January 24, 1926, at 9h 34m Pacific standard time. The image on the right is a direct photograph of the sun, obtained simultaneously with hydrogen ($H\alpha$) image on the left. This eruption was detected independently in Pasadena with the spectrohelioscope.

produce the spots and their magnetic fields. These vortices in the photosphere are accompanied by secondary vortices in the overlying atmosphere, recorded (as in Fig. 10) by the spectroheliograph. From a preliminary study⁶ it appears that the direction of whirl in about 80 per cent. of the high-level vortices accompanying single spots (or the preceding spots of bipolar groups) corresponds with that of terrestrial storms, and does not reverse at sunspot minima.

The above results were derived from an examination of spectroheliograms, but I have found the spectro-

helioscope should greatly assist in determining the true relationship between solar eruptions and terrestrial auroras and magnetic storms. If, as I hope, an inexpensive instrument can be built for the use of amateurs, the chances of detecting the exact moments of critical outbursts will be greatly multiplied. A small spectrohelioscope for this purpose, and improved oscillating and rotating slits to replace the oscillating bar hitherto employed with the 13-foot spectrohelioscope, are now under construction and will soon be ready for trial.

⁵ "Sunspots as Magnets, and the Periodic Reversal of their Polarity," NATURE, January 19, 1924, p. 105.

⁶ Hale, "A Test of the Electromagnetic Theory of the Hydrogen Vortices surrounding Sunspots," Proc. Nat. Acad. Sciences, 11, 691-696, 1925.

⁷ For a brief description of these observations, and some suggestions regarding other applications of the spectrohelioscope, see "Visual Observations of the Solar Atmosphere," Proc. Nat. Acad. Sciences, 12, 286-295, 1926.