

THE SPECTROHELIOSCOPE AND ITS WORK¹

PART III. SOLAR ERUPTIONS AND THEIR APPARENT TERRESTRIAL EFFECTS

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ABSTRACT

In co-operative observations with the spectrohelioscope, to be made at many stations distributed around the world, occasional violent eruptions on the sun's disk call for first attention. Many of these phenomena are described and illustrated in this paper. Most of them were photographed with the spectroheliographs of the Kenwood, Yerkes, Mount Wilson, South Kensington, Kodaikanal, and Meudon Observatories, which should be used in connection with the chain of spectrohelioscopes for their detection and study.

Several of these eruptions were followed after an (average) interval of about twenty-six hours by violent terrestrial magnetic storms and brilliant auroras. The principal theories of these phenomena, all of which ascribe them to the influence of solar disturbances, are briefly outlined.

The paper includes a list of the 23 widely distributed observatories where spectrohelioscopes are already in use or will soon be erected. Other spectrohelioscopes will be available later at additional stations. It will thus be possible to inaugurate a comprehensive series of observations under the auspices of the International Astronomical Union.

In previous papers of this series I have described the spectrohelioscope and its adjustments and have given a few observations of the hydrogen flocculi near sun-spots made with its aid.² Deferring for the present further discussion of other similar observations, I have thought it advisable to devote the present paper to an account of some exceptional outbursts on the sun's disk, most of which have been followed by brilliant auroras and widespread magnetic storms. Although certain important discrepancies remain unexplained, the evidence seems to favor the view that the observed solar eruptions are directly connected with these terrestrial phenomena.

The spectrohelioscope and the spectroheliograph easily reveal in the light of hydrogen or calcium the sudden appearance and the rapidly changing forms of eruptions on the sun's disk. As these outbursts may not last more than a few minutes, an adequate chain

¹ *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 425.

² Part I: "History, Instruments, Adjustments, and Methods of Observation," *Mt. Wilson Contr.*, No. 388; *Astrophysical Journal*, **70**, 265, 1929; Part II: "The Motions of the Hydrogen Flocculi near Sun-Spots," *Mt. Wilson Contr.*, No. 393; *Astrophysical Journal*, **71**, 73, 1930.

of instruments, distributed around the earth and used in a co-operative plan, is needed to make the solar record sufficiently complete for comparison with records of the various terrestrial phenomena in question. During the last few years twenty-three spectrohelioscopes and coelostat telescopes of the type described in the first paper of this series have been built or ordered for the observatories listed on page 411, and others will soon be added. It is therefore evident that a fairly comprehensive co-operative observational scheme is now feasible.

It is important that all signs of eruption on the disk, especially those observed near the central meridian of the sun, be followed and carefully analyzed. Many small eruptions may break out suddenly and subside within a short time, but others, of similar appearance in their initial stages, may develop into vast outbursts, of intense brilliancy and of great importance from a geophysical standpoint. If, as the available evidence so strongly suggests, rapid changes in intense flocculi near the central meridian of the sun are usually followed by terrestrial disturbances, it is highly desirable that all the significant facts, such as their times of appearance, maximum development, and disappearance, and their approximate heliographic position, form, area, motions, and intensity at successive stages, be learned as soon as possible. The various theories hitherto proposed, especially those which attribute to radiation pressure the flight of erupted gases from the sun to the earth, can then be thoroughly tested, thus greatly facilitating other studies of solar and terrestrial relationship. Existing data are very incomplete, as might be expected because of the small number of observations made daily and the distribution of properly equipped observers in longitude. The spectrohelioscopes now available are more numerous, better distributed in longitude, and much quicker in action than the few spectroheliographs in daily use. They also have the advantage of permitting the instant change in wave-length of the light under observation, thus enabling effects often missed with the spectroheliograph to be detected and analyzed. By means of a simple attachment, to be described in a later paper, they can be quickly adapted for photographically recording unusual phenomena in light of any wave-length.

Although accounts of many of the solar eruptions described in the following pages have been published, they are scattered through English, American, and French journals, covering a period of nearly seventy years, and are therefore often overlooked by physicists, geophysicists, and even by astronomers interested in widely different observational or theoretical aspects of the subject. The original papers should always be consulted when available, but an illustrated summary may be useful in calling attention to the further possibilities of research.

“A SINGULAR APPEARANCE SEEN IN THE SUN ON
SEPTEMBER 1, 1859”

Carrington's classic volume, *Observations of the Spots on the Sun* (London, 1863), refers on page 167 to a remarkable observation lasting about five minutes which he described and illustrated in the *Monthly Notices of the Royal Astronomical Society*, 20, 13, 1859. While making his daily record of the forms and positions of sun-spots on September 1, 1859,

within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram (Fig. 1) by the letters *A* and *B*, and of the forms of the spaces left white. My first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by which the general image is thrown into shade, for the brilliancy was fully equal to that of direct sun-light; but, by at once interrupting the current observation, and causing the image to move by turning the R.A. handle, I saw I was an unprepared witness of a very different affair. I thereupon noted down the time by the chronometer, and seeing the outburst to be very rapidly on the increase, and being somewhat flurried by the surprise, I hastily ran to call some one to witness the exhibition with me, and on returning within 60 seconds, was mortified to find that it was already much changed and enfeebled. Very shortly afterwards the last trace was gone, and although I maintained a strict watch for nearly an hour, no recurrence took place. The last traces were at *C* and *D*, the patches having travelled considerably from their first position and vanishing as two rapidly fading dots of white light. The instant of the first outburst was not 15 seconds different from 11^h18^m Greenwich mean time, and 11^h23^m was taken for the time of disappearance. In this lapse of 5 minutes, the two patches of light traversed a space of about 35,000 miles, as may be seen by the diagram, which is given exactly on a scale of 12 inches to the sun's diameter. On this scale the section of the earth will be very nearly equal in area to that of the detached spot situated most to the north in

the diagram, and the section of *Jupiter* would about cover the area of the larger group, without including the outlying portions. It was impossible, on first witnessing an appearance so similar to a sudden conflagration, not to expect a considerable result in the way of alteration of the details of the group in which it occurred; and I was certainly surprised, on referring to the sketch which I had carefully and satisfactorily (and I may add fortunately) finished before the occurrence, at finding myself unable to recognize any change whatever as having taken place. The impression left upon me is, that the phenomenon took place at an elevation considerably above the general surface of the sun, and, accordingly, altogether above and over the great group in which it was seen projected.

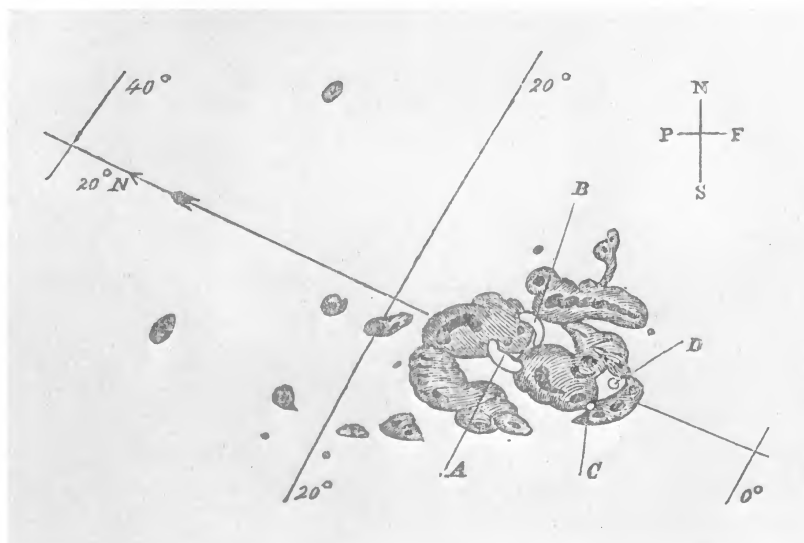


FIG. 1.—September 1, 1859, 11^h18^m G.M.T.; sun's diameter = 289 mm (Carrington)

Both in figure and position the patches of light seemed entirely independent of the configuration of the great spot, and of its parts, whether nucleus or umbra.

[Mr. Carrington exhibited at the November Meeting of the Society a complete diagram of the disk of the sun at the time, and copies of the photographic records of the variations of the three magnetic elements, as obtained at Kew, and pointed out that a moderate but very marked disturbance took place at about 11^h20^m A.M., Sept. 1st, of short duration; and that towards four hours after midnight there commenced a great magnetic storm, which subsequent accounts established to have been as considerable in the southern as in the northern hemisphere. While the contemporary occurrence may deserve noting, he would not have it supposed that he even leans towards hastily connecting them. "One swallow does not make a summer."]

Hodgson, who fortunately observed this phenomenon, describes it in the same number of the *Monthly Notices* (p. 15) as follows:

While observing a group of solar spots on the 1st September, I was suddenly surprised at the appearance of a very brilliant star of light, much brighter than the sun's surface, most dazzling to the protected eye, illuminating the upper edges of the adjacent spots and streaks, not unlike in effect the edging of the clouds at sunset; the rays extended in all directions; and the center might be compared to the dazzling brilliancy of the bright star α *Lyrae* when seen in a large telescope with low power. It lasted for some five minutes, and disappeared instantaneously about 11:25 A.M.

The magnetic storm referred to by Carrington was described by Balfour Stewart,¹ who remarked on "its excessive violence and length of duration" and the accompanying "auroral displays of almost unprecedented magnificence," observed in Europe, America (as far south as Cuba), and Australia. From an analysis of the photographic magnetic records obtained at the Kew Observatory, it appears that we have two distinct well-marked disturbances, each commencing abruptly and ending gradually, the first of which began on the evening of August 28, and the second on the early morning [5:00 A.M.] of September 2. These two great disturbances correspond therefore in point of time to the two great auroral displays already alluded to.

After describing these magnetic phenomena he adds:

But, besides these two remarkable disturbances into which it divides itself, this great storm comprehends a minor disturbance, not approaching these two in extent, but yet possessing an interest peculiar in itself, which entitles it to be mentioned. . . . This disturbance occurred as nearly as possible at 11^h15^m A.M. Greenwich mean time, on September 1, 1859, affecting all the elements simultaneously, and commencing quite abruptly.

After quoting the greater part of Carrington's paper and referring to the conclusions of Sabine regarding the relationship between sunspots, auroras, earth currents, and magnetic disturbances, Stewart suggests that the terrestrial effects are due to sudden variations in the intensity of a primary current in the sun, which induce secondary currents along the surface of the earth and the upper strata of the atmosphere. The question was thus raised whether Carrington's phenomenon was directly responsible for a small instantaneous effect on the earth's magnetic field, or for the much greater magnetic disturbance that began nearly eighteen hours later and corresponded in time to one of the two brilliant auroral displays.

¹ *Philosophical Transactions of the Royal Society of London*, 151, 423, 1861.

Professor Young's preference for a direct electromagnetic action on the earth, propagated with the velocity of light, of every intense solar disturbance was partly due to his experience at Mount Sherman in 1872, where he observed several brilliant distortions of the $H\alpha$ line near a sun-spot at the sun's eastern limb that closely coincided in time with "peculiar twitches of the magnets in England." With characteristic caution, however, he quoted Lord Kelvin's conclusion (1892) against the possibility of such magnetic action of the sun and added:

Of course, as has been said, no two or three coincidences such as have been adduced are sufficient to establish the doctrine of the sun's immediate magnetic action upon the earth, but they make it so far probable as to warrant a careful investigation of the matter—an investigation, however, which is not easy, since it implies a practically continuous watch of the solar surface.¹

Speaking of the well-known but still obscure parallelism between curves of magnetic intensity and auroral and sun-spot frequency, he also acutely remarked, many years before the discovery of radiation pressure, that perhaps the solar effect is "in some way kindred with the action which drives off the material of a comet's tail, and proves that other forces besides gravitation are operative in interplanetary space."²

THE SOLAR ERUPTION OF JULY 15, 1892

My own experience in this field began on July 15, 1892, when a series of photographs of a remarkable solar disturbance was obtained with the recently mounted spectroheliograph of the Kenwood Observatory, Chicago.³ The scene of the disturbance was a large and active sun-spot, which had first appeared as a few small dots at about 32° south latitude on June 13, during the previous rotation. On July 8 it had returned to the east limb of the sun, and on July 15 it was near the central meridian.

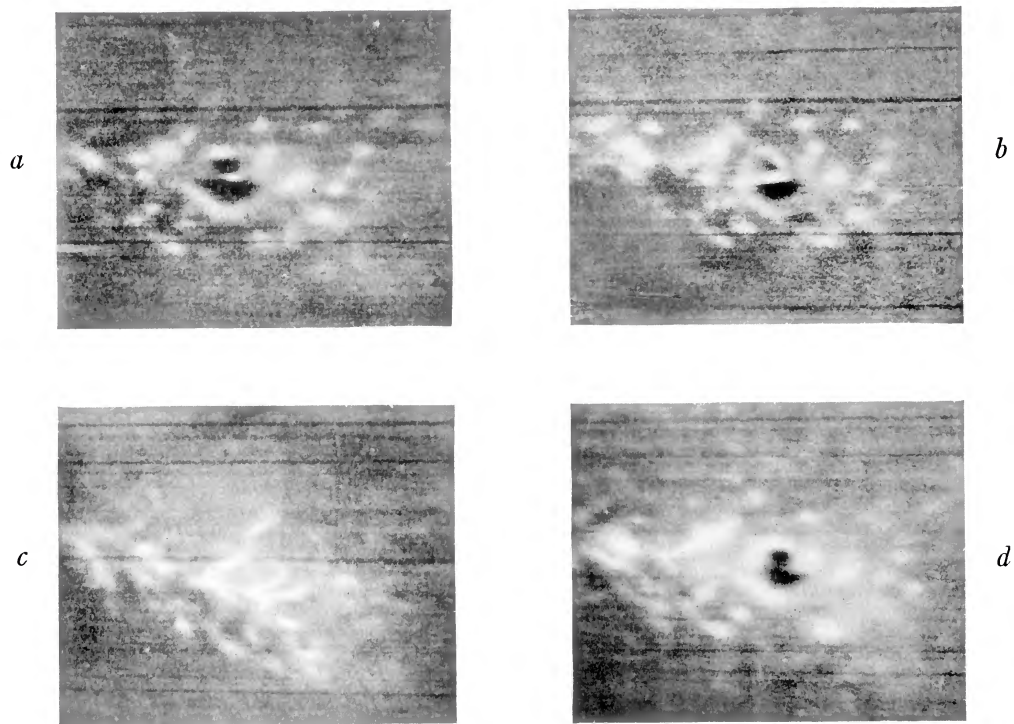
The first photograph, taken with the calcium (K) line at about 16^h58^m G.C.T. (Plate IVa), showed nothing unusual, except that the bridge between the northern and southern umbrae of the spot was

¹ *The Sun* (rev. ed.), pp. 166-169, 1895.

² *Ibid.* (2d ed.), p. 156, 1884.

³ Hale, "A Remarkable Solar Disturbance," *Astronomy and Astrophysics*, **11**, 611, 1892.

PLATE IV



Solar eruption of July 15, 1892, photographed with the calcium line K_2 ; sun's diameter = 207 mm (Kenwood Observatory): *a*, 16^h58^m; *b*, 17^h10^m; *c*, 17^h37^m; *d*, 19^h50^m G.C.T.

brighter than usual. The next exposure, made about twelve minutes later, showed a very different state of affairs. Extending between the umbrae, in a direction slightly inclined to the sun's equator, was a perfectly straight and exceedingly brilliant object, which expanded slightly at its eastern extremity and turned sharply toward the north, terminating abruptly in a brilliant ball just east of the center of the northern umbra. The sudden formation of this remarkable object did not seem to affect the spot or the general group of flocculi surrounding it, which showed no material change of form. As the plates were not developed immediately, the occurrence of the eruption was not known at once, and the next photograph was not taken until about 17^h37^m G.C.T. Meanwhile, an entire transformation had taken place in the luminous phenomenon, which now completely covered the spot and a large area surrounding it. About an hour later I observed the *H α* line visually in the spectrum of the spot and found, at some distance to the west of the group, that the reversals were so brilliant that the form of the hydrogen cloud could be very well seen through a widely opened slit. Spectra of various parts of the spot photographed at 19^h and spectroheliograms taken at 19^h31^m and 19^h40^m G.C.T. showed the flocculi surrounding the spot to be of the same form as before the disturbance, which had then completely disappeared. It therefore began at about 16^h58^m, reached the greatest recorded stage of its development in about 39^m, and vanished about two hours after its first appearance.

I am indebted to Mr. J. A. Fleming, acting director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, for copies of magnetograms showing the magnetic storms associated with many of the solar phenomena described in this paper. Those for July, 1892, which are from the records of the Royal Observatory, Greenwich, show marked disturbances on July 12, 14, and 17, and a much greater one on July 16. The latter commenced suddenly shortly after noon (about 12^h30^m) on July 16, and continued with somewhat reduced amplitudes until about 17^h30^m; a violent series of deflections then began, continuing with varying intensity until about 19^h8^m, when another violent disturbance began and lasted nearly forty minutes. The storm then suddenly moderated, although marked but less violent deflections occurred later.

The sudden beginning at about 12^h30^m was approximately nineteen and a half hours after the first of the Kenwood exposures, but the interval between this first spectroheliogram and the beginning of the violent magnetic storm at 17^h30^m was about twenty-four and a half hours. Further details regarding the various phenomena photographed with the Kenwood spectroheliograph near this and other spot groups in June and July; Rudaux's direct observations of the eruption of July 15; my own observations of a brilliant aurora on the evening of July 16; Townsend's visual spectroscopic observations of the same spot on various dates; and Sidgreaves' account of the July solar disturbances and magnetic storms—all may be found in the papers cited below.¹ The chief points suggested by these observations are as follows:

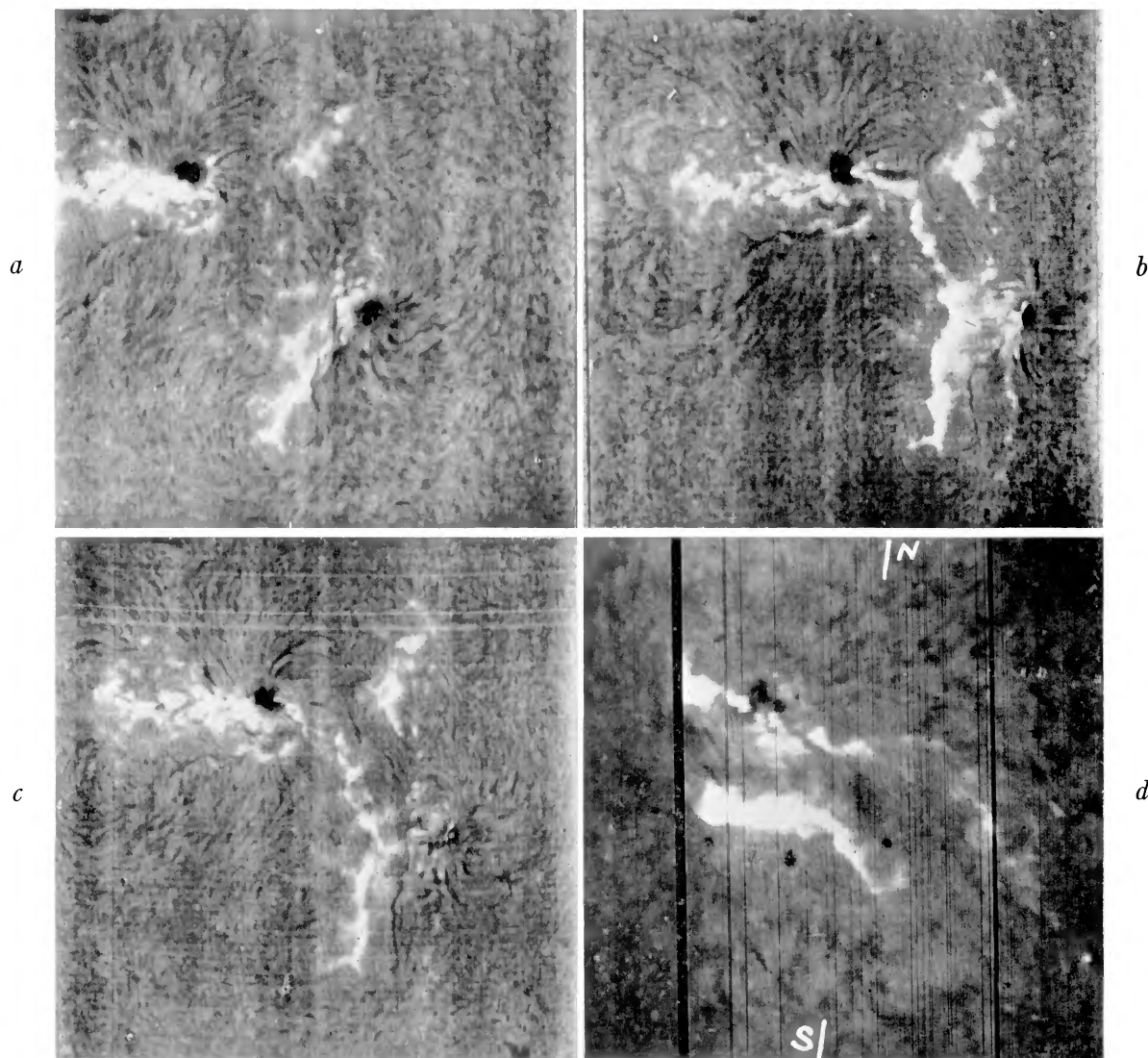
1. Eruptions on the sun's disk apparently associated with magnetic storms are characterized by increased intensity of the Ca^+ and hydrogen lines, and may therefore be observed spectroscopically or photographed with the spectroheliograph.

2. Sidgreaves remarked that "on the 11th, the day Mr. Townsend observed the remarkable reversals of the C ($H\alpha$) line over the spot at about 12^h15^m P.M., G.M.T., a single sharp upward movement both on the declination and horizontal force magnets alone interrupted their otherwise quiescent state." At the time of my own observation of July 15, according to Sidgreaves, "there was not the slightest disturbance on the vertical force and declination magnets. There was, however, a slight trembling in the horizontal force magnet," but the actual magnetic storm did not begin until the following day. On the whole, the hypothesis that the effect of a violent solar eruption is transmitted to the earth with the velocity of light received little or no support from these observations.

3. The occurrence of a terrestrial magnetic storm about nineteen and a half hours after the beginning of the solar eruption and a much more violent storm about five hours later may be compared with

¹ Hale, "On the Condition of the Sun's Surface in June and July, 1892, as Compared with the Record of Terrestrial Magnetism," *ibid.*, p. 917; "Magnetic Disturbances and Auroras," *ibid.*, p. 617; Townsend, "The Solar Disturbance of July, 1892," *ibid.*, p. 815; Sidgreaves, "The Solar Disturbance of July, 1892, and the Accompanying Magnetic Storms," *ibid.*, p. 819.

PLATE V



a, b, c.—Solar eruption of September 10, 1908, photographed with the hydrogen line $H\alpha$, at $5^{\text{h}}36^{\text{m}}$, $8^{\text{h}}25^{\text{m}}$, and $9^{\text{h}}48^{\text{m}}$ G.M.T., respectively; sun's diameter = 168 mm (Yerkes Observatory).

d.—Eruption of May 12, 1909, photographed with $H\alpha$ at $14^{\text{h}}45^{\text{m}}$ G.C.T.; sun's diameter = 226 mm (Mount Wilson Observatory).

the interval of about $17^{\text{h}}42^{\text{m}}$ between the apparent solar and terrestrial effects noted in Carrington's case, though the latter value might have been greater if his observations had been made with calcium or hydrogen light.

4. Another resemblance with Carrington's observation lies in the fact that both spots in which the outbursts occurred were near the central meridian of the sun.

5. Still another agreement with Carrington is the absence of any change in the spot after the eruption, which led me to infer, in the first paper cited, that "we seem to be dealing with an extremely brilliant eruptive prominence."

6. On this assumption, the visibility of Carrington's outburst in the white light of the direct solar image may be ascribed to the presence in the prominence of a very bright continuous spectrum, such as has often been observed in brilliant eruptive prominences at the sun's limb.

7. It should be added, however, that either through lack of observations or for some other cause no solar outburst corresponding to that of July 15 is known to account for the other magnetic storms recorded in July, 1892, at Greenwich.

8. Sidgreaves, noting that three magnetic storms coincided with three separate meridian passages of the same spot, remarked that this "only serves to confirm the opinion expressed in the *Stonyhurst College Observatory Report* for 1883 that 'there is some evidence to show that the aurorae and magnetic storms synchronize rather with particular classes of spots than with solar disturbances generally.' "

THE ERUPTION OF SEPTEMBER 10, 1908

This important eruption (Plate V), which extended across the solar equator so as to connect two large spots in the northern and southern hemispheres, was photographed in most of its phases by Messrs. Fox and Abetti with the Rumford spectroheliograph of the Yerkes Observatory.¹

The first plates of September 10 were the routine calcium exposures. These showed considerable activity in the spot groups, principally in the eruptions in

¹ "Interaction of Sun-Spots," *Astrophysical Journal*, 29, 42, 44, 1909.

the northern group. The $H\alpha$ plates of 5^h36^m and 5^h58^m G.M.T. revealed an intensification of the eruptions in the northern group,¹ a brightening of the flocculi following the southern group, and a slight strengthening of the isolated flocculus preceding the northern group, but gave no intimation of the pending outburst. Visual, spectroscopic examination at 7^h30^m G.M.T. indicated a violent uprush of hydrogen immediately behind the southern spot and also at some distance following. A plate was immediately exposed, 7^h52^m . On this and subsequent plates tremendous changes were found. A brilliant eruption had occurred behind and in contact with the southern spot. Somewhat more remotely following, a still greater and more striking eruption was in progress, extending east and south like a great leg, brilliant to its toe, and stretching to the north in two branches, one nearly to the neighboring spot, the other a chain of brilliant eruptions reaching toward the isolated flocculus. This flocculus, the remains of an expired spot, had increased greatly in intensity and had extended arms toward the approaching chain of eruptions and toward the northern spot. From the northern spot an eruptive arm stretched to meet the eruptions advancing from below and from the flocculus. This is well seen at 8^h13^m . At 8^h25^m the connection of the northern and southern spots was completed.

After this consummation the subsidence to relative tranquillity was as rapid as the rise. Examination of the line $H\alpha$ at 9^h30^m revealed descent in the eruptive regions behind the southern spot. Measurement of the displacement of the line on the photographs made at this time gives velocity of descent behind the spot as about 100 km per second and 170 km in the great eruption due east of the spot. The result of this is seen on the plates at 9^h39^m and 9^h48^m in the obliteration of the eruptive feature behind the spot and in the decline in the great eruption. Other plates exposed later showed a continued decline. The whole display lasted less than four hours and fortunately the history of it as shown on our plates is nearly complete. . . .

Several investigators have expressed the opinion that the source of terrestrial magnetic storms is in the eruptions about the spots rather than in the spots themselves. Hale in discussing the magnetic fields which he has recently detected in sun-spots concludes, from the rapid diminution of strength of field with altitude, that terrestrial magnetic storms are probably not caused directly by these fields² and states: "Their origin may be sought with more hope of success in the eruptions shown on spectroheliograph plates in the regions surrounding spots." A disturbance of the magnitude of this one of September 10 might have been expected to produce noticeable effects on the earth. In *Nature* of September 24 Chree describes a large magnetic storm which occurred on September 11, beginning at 9^h47^m . The lag in time between the solar and terrestrial storms, something over twenty-six hours, is not consistent with the view of Young³ and of Nordmann⁴ that the magnetic impulse travels with the speed of light; but is more in harmony with the observations of Maunder⁵ and of Riccò,⁶ who find retardations of 26^h and 45^h5 respectively. The lags found by Maunder and Riccò, though both rest on the central meridian passage of sun-spots, are not

directly comparable, for Maunder determined the lag to the middle of the magnetic storm and Riccò to the maximum.

¹ Dennett observed an eruption in this group on September 9 lasting from 19^h45 to 20^h30 G.M.T. (*Observatory*, 31, 388, 1908).

² *Astrophysical Journal*, 28, 341, 1908; see also Schuster, *Nature*, 78, 663, 1908; *Monthly Notices of the Royal Astronomical Society*, 65, 187, 1904.

³ *Nature*, 7, 109, 1872.

⁴ *Journal de Physique* (4), 3, 115, 1904.

⁵ *Monthly Notices of the Royal Astronomical Society*, 64, 207, 1903-1904.

⁶ *Memorie della Società degli Spettroscopisti Italiani*, 33, 38, 1904.

The Greenwich magnetograms for this storm show a sudden beginning, as stated by Chree, on September 11 at 9^h47^m, G.M.T. Great deflections occurred between midnight and about 8:00 A.M. on September 12.

The conclusions of Maunder and Riccò refer, not to such eruptions as are described in this article, but to large sun-spots. From an extensive statistical investigation of the relationship between sun-spots and terrestrial magnetic storms, Maunder found that such storms begin during a period of from thirty-four hours before to eighty-six hours after the passage of a group of spots across the central meridian of the sun. The mean time of the beginning of a magnetic storm is twenty-six hours after that of central meridian transit.¹ Maunder pointed out in 1892, however, that while in many cases terrestrial magnetic storms are undoubtedly connected with large sun-spots,

spots as important have been seen upon the sun, and the magnets have scarcely fluttered, and storms as distinct have occurred when there have been only few spots, and those but small, upon the visible disk of the sun. . . . The conclusion to my own mind seems to be that though Sun-spots are the particular solar phenomena most easily observed, we must not infer therefore that their number and extent afford the truest indications of the changes in the solar activity which produce the perturbations we remark in our magnetic needles.²

Moreover, in a letter dated March 17, 1892, Tacchini wrote me from Rome regarding the Kenwood spectroheliograph:

Comme j'ai noté dans le dernier numéro des *Memorie*, j'ai montré autrefois, qu'avec plus de probabilité, ce sont les phénomènes chromosphériques et ceux qui se produisent dans l'atmosphère du Soleil, qui correspondent aux phénomènes magnétiques terrestres; de manière que, si une tache passe sur le

¹ *Monthly Notices of the Royal Astronomical Society*, 64, 205, 1904, and 65, 2, 1904.

² Quoted from *Knowledge in Astronomy and Astrophysics*, 11, 528, 1892.

disque dans un état de calme, nous n'aurons pas des aurores ni des perturbations magnétiques correspondantes; au contraire, si un jour sur la tache ou sur les facules auront lieu des phénomènes extraordinaires, que nous ne pouvons pas constater avec les moyens employés jusqu'à présent, on aura encore sur la terre et sur les autres planètes des perturbations. Or c'est avec vos observations qu'on pourra vérifier si un groupe de taches ou de facules en traversant le disque, se maintient calme toujours, ou si dans un temps donné se sont manifestés des phénomènes extraordinaires.¹

THE ERUPTION OF MAY 12, 1909

One of the most striking cases of a large eruption on the sun's disk followed by an intense magnetic storm is shown on two *H α* spectroheliograms taken by Ellerman with the 60-foot tower telescope at Mount Wilson on May 12, 1909. The large spot group with which it was associated (Greenwich 6668 and 6669, a return of Greenwich 6658), at about 15° south latitude, had been marked by two small but bright hydrogen eruptions when near the east limb on May 9, and continued to give further evidences of activity. The first *H α* plate, taken on May 12 at $14^{\text{h}}35^{\text{m}}$ G.C.T., when the group was about 15° east of the central meridian, showed two very large and brilliant calcium flocculi, one partly overlying the largest spot of the group, the other, even more brilliant but not so long, nearer the preceding spot. A second *H α* plate, taken ten minutes later, is reproduced as Plate Vd. This shows several marked changes when compared with the earlier plate. Unfortunately no more *H α* spectroheliograms were made that day, though the spot group continued to give evidence of definite but much less marked eruptive activity as it crossed the disk.

An intense magnetic storm began at Greenwich on May 14, at $4^{\text{h}}9$ G.C.T., or thirty-eight and three-tenths hours after our first spectroheliogram was taken on May 12. This disturbance, which lasted thirty-nine hours, was an exceptional one, classed at Greenwich as a "great" storm.

THE ERUPTION OF SEPTEMBER 24, 1909

In a paper on "The Magnetic Storm of September 25, 1909, and the Associated Solar Disturbance"² Dr. W. J. S. Lockyer describes

¹ *Ibid.*, p. 437.

² *Monthly Notices of the Royal Astronomical Society*, 70, 12, 1909.

and illustrates a series of calcium spectroheliograms, obtained at the South Kensington Observatory, of a large spot at south latitude 5° , which crossed the central meridian on September 23:

To continue and end the history of this group as recorded in calcium light we now come to September 24. On that day four photographs of the disc were secured, and no others were possible until October 5, in consequence of unfavorable weather.

September 24, 10^h5^m50^s.—This photograph shows a complete transformation of the large flocculus group in comparison with those taken previously. The two most striking features are the great increase in intensity, and the nearly complete change of form. The flocculus group towards the south-west maintains its form and intensity, as exhibited on the 21st and 22nd, showing that the disturbed area was local to the other group. Special attention should be drawn to the great brilliancy of the calcium cloud in the north-western quadrant of the group, which seems to have the appearance of a portion of a spiral.

A photograph taken about five minutes later indicates definite changes of form and intensity, while photographs made at 11^h11^m and 11^h16^m show a marked reduction in the intensity and area of the bright flocculus recorded on the first plate. Of this Lockyer states:

The gradual crescendo of activity up to the 22nd, and the abrupt change in appearance of the group between 10^h10^m and 11^h11^m on the morning of the 24th, suggest that possibly 10 o'clock on the 24th might approximately represent the time of greatest activity.

The series of photographs here illustrated shows, I think, with little doubt, that we are, in photographs Nos. 5 and 6, in the presence of a large active prominence, situated above the ordinary solar level which produces the usual "K₂" flocculi.

An intense magnetic storm, described by Chree as probably not exceeded in range of the elements during the previous twenty years, was shown on the Kew records to begin at 11^h43^m A.M. on September 25, ending at 8^h30^m P.M. on the same day. According to Lockyer, Sidgreaves stated the storm to be at its height between 3^h30^m and 5^h30^m P.M. on the same date. Lockyer therefore took 4^h30^m P.M. as the approximate time of its greatest intensity, and gave twenty-five and three-quarters and thirty and a half hours, respectively, as the intervals between the maximum of the eruption and the beginning and the maximum of the magnetic storm.

The time of the beginning of this solar eruption is not exactly known, as it was in progress when Lockyer's first photograph was

taken on September 24, and no spectroheliograms were made at South Kensington on the previous day. Holmes observed a brilliant reversal of the $H\alpha$ line in this spot at 11^h30^m G.C.T., on September 24, and this was also seen by Fowler (with open slit) at 12^h20^m on the same day. The Mount Wilson spectroheliograms made with the H_2 line of calcium on September 23, 24, and 25, and those made with the $H\alpha$ line of hydrogen on September 24 and 25 show definite signs of activity in this spot group, but the eruption photographed by Lockyer was missed. Slocum, however, noted at the Yerkes Observatory that "the calcium flocculi over the spot present (on September 24) a marked spiral form, with several brilliant eruptions on the branches and outside the spiral." On the return of this spot in October he found it to be still active, with occasional small eruptions. Slocum also remarked that the spot was about 20° east of the central meridian when a brilliant auroral display was observed.¹ The magnetometer at Greenwich was "very active" on this date. Perhaps it should be added that while the magnetograms obtained at Lu-Kia-Pang, China, were incomplete (off the scale) during part of the storm, all three elements show the sharp beginning to be close to the time given by Chree, while the maximum range in declination occurred at about 13^h20^m G.C.T. on September 25.

ERUPTIONS PHOTOGRAPHED IN JUNE, 1915

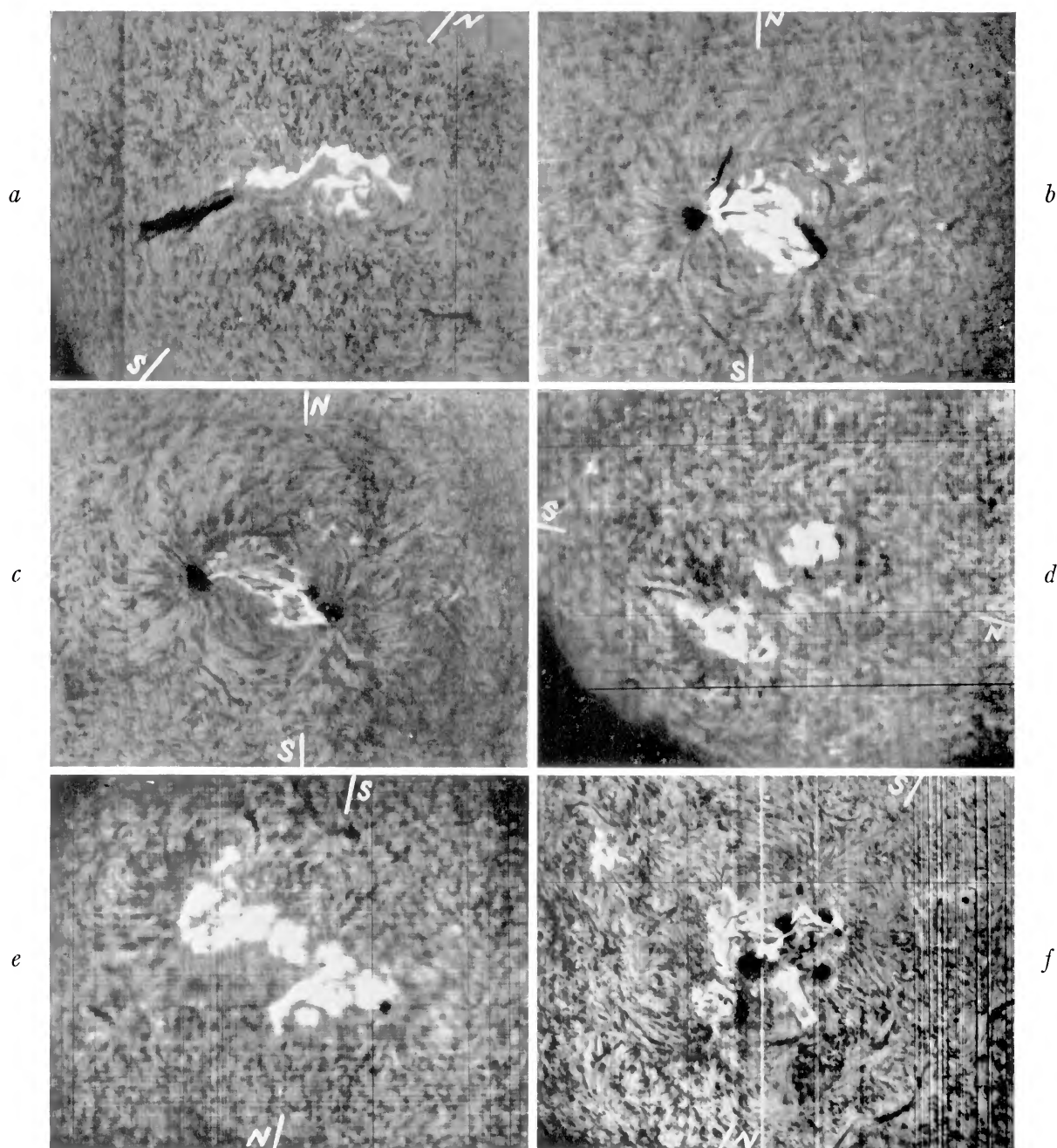
The Mount Wilson direct photographs of the sun indicate that between June 15, 15^h49^m and June 16, 14^h33^m G.C.T. a large spot suddenly developed in a very active group then east of the central meridian, which it crossed on June 18. This group (Greenwich 7299), at about 2° north latitude, showed many bright eruptions on our $H\alpha$ spectroheliograms during its passage over the disk, but as none of these attained great size, it is impossible to connect any of them clearly with the intense magnetic storm² that began (Cheltenham Magnetic Observatory) at 13^h45^m G.C.T. on June 17 and continued about thirty-two hours.

Cortie had previously stated that both the activity and the heliographic latitude of a spot seem to determine its influence on terres-

¹ *Astrophysical Journal*, 31, 26, 1910.

² *Journal of Terrestrial Magnetism*, 20, 77, 1915.

PLATE VI



Solar eruptions photographed with the hydrogen line $H\alpha$; sun's diameter = 169 mm (Mount Wilson Observatory).

a.—November 10, 1916, 15^h40^m G.C.T.

b.—February 7, 1917, 15^h59^m G.C.T.

c.—February 8, 1917, 15^h44^m G.C.T.

d.—February 14, 1917, 16^h6^m G.C.T.

e.—February 16, 1917, 15^h54^m G.C.T.

f.—August 8, 1917, 14^h23^m G.C.T.

trial magnetism.¹ Commenting on this particular group, with the Yerkes and Mount Wilson spectroheliograms before him, he remarked that "the conditions of great disturbance, and favorable position relatively to the earth, were both fulfilled." After noting the rapid changes in the group on June 16 and 18 and the eruptive activity shown by both sets of photographs, he emphasized the low latitude of the group, which corresponded almost exactly with the heliographic latitude of the earth, and added: "A violent magnetic storm, the greatest so far recorded during the present solar cycle, took place on June 17, which was accompanied by fine displays of Aurora Borealis in North America, and of Aurora Australis in New Zealand."²

It should be noted that other active spot groups, some of which showed minor eruptions, were on the sun's disk at this period. One of these, at about 17° north latitude (Greenwich 7304, June 15-27), which was of great size when it crossed the central meridian on June 21, showed a large bright flocculus connecting its preceding and following members on June 22, and other eruptive phenomena on June 23, 24, and 25. Another long stream at about 20° south latitude (Greenwich 7313, June 19-July 1) also showed marked signs of eruptive activity on some days, but not (on our plates) when near the central meridian.

THE ERUPTION OF NOVEMBER 10, 1916

This eruption would have been especially well adapted for study with the spectrohelioscope if that instrument had then been available, because of the partial superposition of a large dark flocculus on the *H α* spectroheliogram (Plate VI*a*). It was associated with the spot group Greenwich 7876 (November 6-17), at about 24° north latitude, which had appeared in two previous rotations as Greenwich 7833 and 7853. This group is described in the *Greenwich Photoheliographic Results* for 1916 as "a composite spot, *a*, with a close companion, *nf*, on November 6 to 8. Numerous small unstable spots form behind *a*, which diminishes but becomes more definite. The group is an irregular stream November 9-15, after which *a* alone

¹ *Monthly Notices of the Royal Astronomical Society*, 73, 149, 1913.

² *Ibid.*, 76, 17, 1915.

remains." The $H\alpha$ spectroheliogram taken at Mount Wilson on November 10 at 15^h40^m G.C.T. shows the considerable area of the eruption, which was approximately 20° east of the central meridian. The long dark flocculus to the east was also shown in part on spectroheliograms taken November 8, 9, 11, and 13, but some of it might have been carried away from the sun by the eruption.

This outburst did not produce a great terrestrial magnetic storm,¹ though there were several minor magnetic disturbances during the month, one of them on November 10.

THE ERUPTIONS OF FEBRUARY 7 AND 8, 1917

The large spot group at 16° south latitude (Greenwich 7977, February 3–16) increased greatly in size and changed rapidly in form as it advanced from the east limb, especially between February 4 and 8. $H\alpha$ spectroheliograms taken at Mount Wilson by Ellerman on February 7 at 15^h59^m G.C.T., and on February 8 at 15^h44^m G.C.T., show the bright eruptions reproduced in Plate VI*b*, *c*.

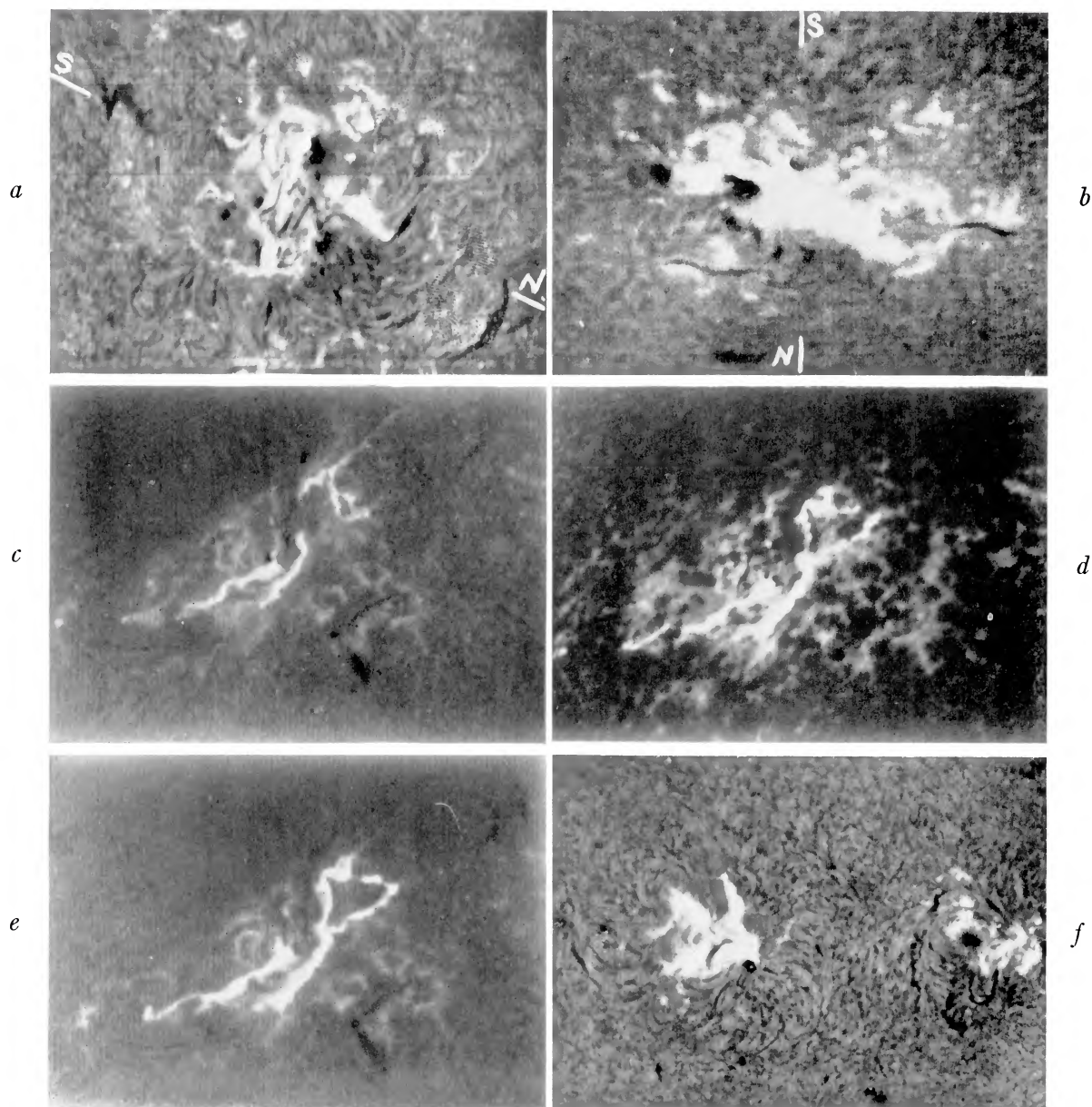
A moderate magnetic storm began at Greenwich on February 7 at 0^h, with maximum from 22^h to 23^h15^m. This was followed on February 8, between 17^h15^m and 19^h, by another moderate storm, with other magnetic disturbances on February 14, 15, and 16. The incompleteness of our solar records renders it impossible to establish any reliable time interval between the solar and terrestrial phenomena. It should be noted, however, that the predominantly arched type of eruption indicated by the photographs suggests that most of the gases fell back upon the sun—a point that the use of a spectrohelioscope, or even a series of spectroscopic observations, might have cleared up.

THE ERUPTIONS OF FEBRUARY 14 AND 16, 1917

On February 14 the above-mentioned spot group was near the west limb, but another smaller though active group at 23° south latitude had reached a point about halfway between the east limb and the central meridian. This was Greenwich 7986 (February 11–21), at about 23° south latitude. A diffuse eruption of moderate intensity is shown closely following the largest spot of this group on

¹ *Journal of Terrestrial Magnetism*, 22, 50, 1917.

PLATE VII



a, b.—Solar eruptions photographed at Mount Wilson August 9, 1917, 15^h13^m, and January 24, 1926, 17^h34^m, G.C.T., respectively; sun's diameter=172 and 148 mm.

c, d, e.—Eruptions photographed at Kodaikanal February 22, 1926, at 8^h36^m, 9^h0^m, and 9^h4^m, I.S.T., respectively; sun's diameter=151 mm.

f.—Eruption photographed at Meudon October 13, 1926, at 13^h15^m G.C.T.; sun's diameter=108 mm.

an *H α* spectroheliogram taken at Mount Wilson by Nicholson on February 14 at 16^h6^m G.C.T. (Plate VI*d*).

Another eruption, somewhat brighter and larger, appears on an *H α* plate taken on February 16 at 15^h54^m G.C.T. (Plate VI*e*). This also followed the leading spot, which had greatly increased in size and was about 13° east of the central meridian at the time of this second spectroheliogram. The weather was unsettled at this period and other spectroheliograms are not available.

There was a slight disturbance of the magnets at Greenwich on February 14 between 20^h15^m and 21^h45^m, but a definite magnetic storm did not break out until February 15. This began at 12^h G.C.T., and lasted twenty-four hours, with its maximum at about 18^h on February 15. Less marked magnetic disturbances, in the form of irregular waves, were also recorded at Greenwich on February 17 from 19^h30^m to 20^h30^m, August 18 from 0^h to 1^h, and August 19 from 1^h45^m to 23^h. It is thus difficult or impossible to fix an exact relationship between these solar and terrestrial phenomena. There was a time interval of about thirty hours between the moderate eruption of February 14 and the outbreak of the magnetic storm of February 15, and an interval of about thirty-five and a half hours between the somewhat brighter eruption of February 16 and the irregular wave (−22) in North Force on February 17, which was not classed among the “days of great disturbance.”

THE ERUPTIONS OF AUGUST, 1917

August, 1917, was an exceptionally disturbed month, both from a solar and from a terrestrial magnetic standpoint. Many small bright eruptions occurred on August 6, 7, and 8 (Plate VI*f*) in the huge northern spot group (Greenwich 8181, August 3–16), and on August 9 at 14^h39^m G.C.T. (Plate VII*a*, 15^h13^m), a large eruption occurred in this group when not far east of the central meridian. This was photographed during the sharp magnetic storm registered at Greenwich, August 9, 4^h, to August 10, 4^h G.C.T. Throughout the greater part of this month, however, the number of active spot groups, sometimes showing several eruptions at once, was too great to permit satisfactory comparisons to be made between individual solar outbursts and the numerous magnetic disturbances, including four

of the eight great storms of the year, given in the Greenwich records. If little or no light is thrown by these observations on the length of the time interval, they help to strengthen the evidence in favor of a direct connection between solar eruptions and terrestrial magnetic effects.

Passing over many cases in the Mount Wilson records which indicate a general relationship but uncertain individual correspondence between solar eruptions and terrestrial magnetic storms, we come to an instance of a more definite nature.

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THE ERUPTIONS OF JANUARY 24 AND 25, 1926

As stated in the introductory article of this series, my first crude spectrohelioscope, after some preliminary tests, was set up in Pasadena at my new Solar Laboratory in January, 1926. After a number of experiments with a variety of slit combinations, focal lengths, etc., the apparatus was still in an undeveloped state when a large bright eruptive prominence was detected on January 24 (Plate VIIb) in and following the largest spot group on the disk, at about 21° north latitude. The details, showing rapid changes in form, were fairly well seen for about twenty minutes after $19^{\text{h}}40^{\text{m}}$ G.C.T., but I was then unfamiliar with the use of the spectrohelioscope in observing complex objects, and was also unable to continue the work that day. During the following morning and part of the afternoon a renewal of this eruption was extremely brilliant; in fact, it was the most remarkable solar phenomenon I have ever seen. The forms of the bright and dark flocculi not only repeatedly changed very materially within a few minutes, but when the oscillating slits were set at different wave-lengths there were extraordinary transformations of structure and brightness. Some of these were of the type described in my last article, showing strong dark hydrogen flocculi descending at high velocities into the two umbrae of the largest spot of the group. I found the D_1 , D_2 , and D_3 lines (with stationary slits) to be brightly reversed in the large spot, while D_3 appeared in regions beyond its boundaries as a dark line, greatly distorted toward the red. Observations of the forms of these helium areas were not very satisfactory, as the multiple slits, then not adjustable in width, were too wide for this line. Nevertheless, some bright and

dark helium flocculi were apparently seen, but no definite structure could be made out with D_1 and D_2 of sodium or b_1 of magnesium. On January 26 the great eruption had ceased, though a very small but brilliant eruption, lasting only a few minutes, was observed on the bridge over the large spot at about 20^h10^m G.C.T. This was followed by the appearance of slender dark flocculi, similar to those illustrated in the first paper in this series.

On January 26 the most intense magnetic storm in five years was recorded at Greenwich and elsewhere. This disturbance commenced at 16^h30^m G.C.T. (when the largest spot was about 27° west of the central meridian), rose to a considerable maximum, and subsided soon after 5^h on the following morning.¹ A brilliant aurora was seen in Norway and North America on the night of January 26. Professor Störmer wrote me as follows from Oslo regarding his observations: "I have been most fascinated by a remarkable aurora here on the 26th January of exceedingly *red* color, like the aurora in 1870. I should like to know from which active part of the sun this aurora was coming."

Unfortunately the exact time interval between the beginning of the solar and the terrestrial disturbances cannot be stated, as it is not certain whether the eruption of January 24 or the much more brilliant one of January 25 was involved.

THE ERUPTION OF FEBRUARY 22, 1926

On February 22, 1926, Dr. Royds and his assistants at the Kodaikanal Observatory obtained several spectroheliograms of an outburst on the sun's disk surpassing in brightness any contained in the whole of the Kodaikanal record extending from 1904. It occurred near the active spot observed on January 24 and 25, then at 23° north latitude and 9° west of the central meridian, approximately where the eruption described above was observed visually at Pasadena on the previous rotation.

Spectroheliograms were begun at 7^h51^m I.S.T. (G.M.T. + 5^h30^m). Fig. 1 is an enlargement from the first $H\alpha$ spectroheliogram at 8^h3^m of a region near the active spot near the center of the figure. The spot's position is 23° N. and 9° W. of the central meridian. Fig. 1 exhibits, in addition to dark markings and the

¹ *Nature*, 117, 208, 1926.

usual bright flocculi, some parts of the flocculi which are much brighter than the rest, but this is not very exceptional. What is very unusual is to see these brighter parts develop into such intense and extensive bright filaments as exhibited in the later photographs.

By 8^h8^m, fig. 2, there is considerable growth in length and intensity; at 8^h36^m, fig. 3 [Plate VIIc], there is further development, the more westerly branch now actually touching the sunspot, whilst the large dark marking seen to the north in figs. 1 and 2 has disappeared in fig. 3. Since the dark marking is restored, though in modified form and extent, in a spectroheliogram taken at 8^h41^m with the slit set on the red edge of the *H α* line, its apparent disappearance from fig. 3 should probably be attributed to Doppler displacement of the darkened *H α* line. The dark marking reappears considerably changed in form in the spectroheliogram taken with the slit central on the *H α* line at 10^h24^m and is maintained thereafter.

Fig. 4 [Plate VIId] is a calcium K₂₃ spectroheliogram taken at 9^h0^m. This spectroheliogram was intentionally under-exposed to prevent the ordinary flocculi from developing into the dense white masses familiar to all who have seen calcium spectroheliograms. In consequence of the under-exposure, the ordinary flocculi appear in only medium brightness, but the relative brilliance of the bright filaments is made clear.

The maximum development in brilliancy of these filaments was reached at 9^h4^m, shown in fig. 5 [Plate VIIe]. Subsequently the filaments persist with some changes of form, but become less brilliant. They were still striking in the last spectroheliogram taken at 15^h6^m.

The bright filaments described were due, of course, to brilliant reversals of the *H α* and K lines. The reversals in the *H α* line were examined visually in the spectroscope; the reversal was not, in general, displaced, but the dark *H α* line was displaced locally by over 2 Å. Mr. S. Balasundaram Iyer, Assistant, making visual observations of disc phenomena with another telescope, found that near the umbra of the spot the D₁, D₂ and *b* lines were also reversed; D₃ was dark to the north of the spot.¹

In his description of the great magnetic storm of February 23–25, 1926, H. W. L. Absalom of the Eskdalemuir Observatory notes that it lasted longer than that of January 26–27, which it followed after an interval of twenty-eight days. The Eskdalemuir records show that the second storm began shortly after 14^h on February 23. The maximum ranges in the N and W components of force occurred at approximately 16^h30^m on February 24. The absolute maximum in vertical force occurred between 16^h14^m and 17^h42^m, during which interval the spot of light was off the photographic paper. The ranges

¹ Royds, *Monthly Notices of the Royal Astronomical Society*, 86, 381, 1926.

in N , W , and V during the earlier part of the storm were distinctly less than the ranges in the latter part. In this respect this storm differed from that of January, in which the extreme ranges and most rapid changes occurred during the first thirteen or fourteen hours.¹

The interval between Dr. Royd's first photograph (February 22, 2^h21^m G.M.T.) and the beginning of the magnetic storm (February 23, shortly after 14^h) was thus about thirty-six hours, while the interval between the maxima of the eruptive and magnetic phenomena was about forty-four and a half hours.

THE ERUPTION OF OCTOBER 13, 1926

The next exceptional eruption on the disk to which attention may be called here is that photographed by MM. D'Azambuja and Grénat at the Meudon Observatory on October 13, 1926.

A cette date, à 13^h15^m (T.U.), une image de la couche supérieure de l'hydrogène ($H\alpha$), obtenue avec le grand spectrohéliographe de Meudon, a révélé la présence d'une masse étendue de gaz d'un éclat tout à fait exceptionnel, dans la région occupée par un des groupes de taches, sur le point de traverser le méridien central.

C'est de beaucoup l'éruption la plus intense qui ait été observée à Meudon où les images de l'hydrogène sont enregistrées d'une manière continue depuis 1909.

Le phénomène paraît avoir été très court. A 11^h5^m, en effet, une épreuve de la couche supérieure du calcium (K_3) n'offrait encore rien de remarquable dans la même région. Une seconde image de l'hydrogène, à 14^h41^m, ne montrait plus que les parties saillantes de la masse de gaz, très diminuées d'éclat.

A 14^h35^m, pendant la phase de déclin, la raie $H\alpha$, observée visuellement, semblait peu déviée de sa position normale, même dans les régions les plus brillantes de l'éruption, marquées par des renversements intenses. Mais elle était doublée en plusieurs points, du côté des grandes longueurs d'onde, par une raie sombre assez fine, annonçant la présence de masses hydrogénées descendant, ou redescendant, sur le Soleil avec une grande vitesse, de l'ordre de 130 km/sec. Ces mouvements de descente se révélaient encore, aussi rapides, sur la dernière épreuve du spectro-enregistreur des vitesses, à 15^h37^m.

L'examen visuel de la raie de l'hélium D_3 , dans la région perturbée, montrait en divers endroits des renversements fins, peu marqués. En un seul point, à 15^h30^m, la raie était estompée et fortement déplacée vers le rouge (vitesse radiale: 150 km/sec.).

Les trois autres groupes de taches ont manifesté aussi, vers le même temps, une forte activité. Le 14 octobre, en particulier, deux groupes, à l'Ouest,

¹ Absalom, *Nature*, 117, 416, 1926.

montraient, sur les images de l'hydrogène, des plages faculaires très intenses. Le plus rapproché du bord révélait même, par l'observation visuelle de $H\alpha$, des mouvements radiaux de même sens et aussi importants que ceux présentés la veille par le groupe voisin du méridien central.

Ces marques d'activité solaire exceptionnelle permettaient de prévoir une perturbation magnétique. Celle-ci s'est produite, en effet, très violente dès le 14 Octobre au soir. Elle a débuté à 20^h, environ 31 heures après l'éruption décelée par le spectrohéliographe, et s'est poursuivie pendant 36 heures. Son maximum d'intensité a été atteint entre 19 et 23^h le 15 Octobre, 48 heures environ après le passage au méridien de la région solaire où s'était montrée l'éruption.¹

Shortly after the first maximum of the magnetic storm, at 21^h15^m, a diffuse aurora was detected by M. Baldet at Meudon, where a much more brilliant aurora, comprising about a dozen fan-shaped rays, was observed through clouds two hours later. This aurora was also seen in Germany and America.

As the solar eruption was apparently of short duration, the authors, as stated above, consider the interval between its appearance and the beginning of the magnetic storm to have been about thirty-one hours.

OTHER SOLAR ERUPTIONS

As the purpose of this paper is chiefly to indicate to observers undertaking work with the spectrohelioscope the characteristic phenomena of certain outstanding eruptions, most of which have been closely followed by magnetic storms, no attempt has been made to enter into an exhaustive examination of all the records. Mention should be given, however, to a few other cases.

One of these was illustrated in a series of lantern slides by Mr. Evershed at a meeting of the Royal Astronomical Society on November 12, 1920. These included

a set of calcium images of the Sun's disc taken on June 30, 1916, showing how an ordinary sun-spot group of no particular interest suddenly becomes the seat of a tremendous disturbance. There is a great evolution of calcium light, superposed apparently upon the flocculi; and it is remarkable that at the same time other brilliant points appear on another spot-group, and at the limb an eruptive prominence was photographed. The very brilliant stage only lasted some 15 minutes, and after it had entirely faded away the flocculi appeared practically unchanged for the rest of that day.²

¹ *Comptes rendus*, 183, 701, 1926.

² *Observatory*, 43, 411, 1920.

According to Newton, who has recently published a list of similar eruptions and magnetic disturbances, no magnetic storm followed this outburst, which was at 12° north latitude and 16° west of the central meridian.¹ Another similar case in Newton's table is an (unpublished) eruption photographed by Evershed at 15° north, 23° west on September 14, 1928, which was followed by only a small magnetic storm after the lapse of four and a half days. At a greater distance from the central meridian (21° S., 44° E.) was the bright hydrogen eruption photographed by Richardson at Mount Wilson on January 23, 1928, followed by a moderate magnetic disturbance between ten and thirty-one hours after its formation.² The brilliant flocculi observed by Newton with the Greenwich spectrohelioscope through clouds on August 12, 1930, at 7° south, 3° west occurred during an unsettled magnetic period, and its connection with a small magnetic storm recorded nearly two days later may be a chance coincidence.

The most interesting solar disturbance hitherto observed with the spectrohelioscope at Greenwich is briefly described in a recent number of *Nature* as follows:

The phenomena observed on Nov. 25 evidently represented the end-on view of an eruptive prominence blown out of the sun's chromosphere with a maximum observed velocity of 450 km./sec. Forty-five minutes before the eruption, an apparently stable dark marking was visible; at $10^{\text{h}}34^{\text{m}}$ G.M.T. the velocity rose within a few minutes from 40 km./sec. to about 400 km./sec. At 11^{h} cloud stopped the observations, but the eruption was then declining, and part of the gaseous structure was descending at about 100 km./sec. Contemporary with the appearance of those rapidly moving masses of hydrogen gas, brilliant patches of hydrogen with little or no radial velocity made their appearance.³

Such a sudden and unexpected rise, at high velocity, of an apparently inactive dark flocculus, then near the center of the disk, merits special consideration.

¹ "An Active Region of the Sun on 1930 August 12," *Monthly Notices of the Royal Astronomical Society*, **90**, 824, 1930.

² "An Exceptional Sun-Spot," *Publications of the Astronomical Society of the Pacific*, **40**, 126, 1928.

³ *Op. cit.*, **126**, 969, 1930. A detailed account of this eruption has since appeared in *Monthly Notices of the Royal Astronomical Society*, **91**, 239, 1930.

Excluding all cases in which the initial phase of the solar eruption was not fairly well known, we have the following approximate time intervals between the beginning of the eruptions and the outbreak of intense magnetic storms:

Solar Eruption	Time Interval (Hours)
September 1, 1859	17.5*
July 15, 1892	19.5†
September 10, 1908	26
February 22, 1926	36
October 13, 1926	31+
	26

* This interval might have been greater if Carrington had observed with calcium or hydrogen light.

† The violent series of deflections did not begin until five hours later.

The mean value of about twenty-six hours, which is probably not very greatly in error, may be compared with Maunder's mean time interval of twenty-six hours between the central meridian passage of large active sun-spots and the beginning of the subsequent magnetic storms.

THEORIES OF THE AURORA

A very brief reference to theories of the aurora will suffice for the purposes of this paper. The early history of the corpuscular theory has been given by Carl Störmer,¹ whose interesting account is partially outlined here.

E. Goldstein suggested in 1881 that the sun emits electrical rays (subsequently considered to be cathode rays), and thus sought to explain the mysterious connection between variations in solar activity and terrestrial magnetism. In 1894 A. Paulsen attributed the aurora to cathode rays, which he supposed to originate in the upper strata of the earth's atmosphere. Two years later K. Birke-land found that a magnetic pole, acting like a lens on parallel light, caused a beam of cathode rays to condense toward a point. He therefore ascribed the aurora to such an effect of the earth's magnetic field on cathode rays coming from the sun. By experimental tests with a spherical electromagnet exposed to a stream of cathode rays, he was able to imitate the principal phenomena of the aurora. S. Arrhenius, in 1900, attributed the repulsion from the sun of electrified particles causing the aurora to the effect of radiation pres-

¹ *Journal of Terrestrial Magnetism*, 22, 23, 97, 1917.

sure. As E. Pringsheim and R. J. Strutt have shown, the repulsive force cannot be due to thermal convection.¹ Nor can it be electrical, because it acts upon neutral as well as ionized atoms.²

Störmer's extensive researches were begun in 1903. Starting from the mathematical investigations of H. Poincaré, and assuming the motions of the earth and sun to be negligible, the earth's field to be that of a uniformly magnetized sphere, and all terrestrial forces other than the earth's magnetism to be absent, he calculated the trajectories of electric corpuscles coming from the sun. The results were so satisfactory that he has since continued his investigations with great activity and success, and tested them by extensive visual and photographic observations in high latitudes. In his later work he has enlarged the range of his researches, and has studied the trajectories of both positively and negatively charged particles moving at various velocities. In this way he has been able to account for the latitude of the zones of maximum auroral frequency and to explain why auroras extending into comparatively low latitudes are always accompanied by magnetic storms.

It is evidently a matter of importance to determine the source, nature, and velocities of the solar particles assumed by this theory and others to be the cause of auroras. The suggestion that high speed β or α particles are emitted by radioactive phenomena was opposed by F. Lindemann, on the ground that they would require incredible radioactivity in the sun, that charged particles having the same sign could not remain together in transit because of electrostatic repulsion, and for other reasons. He therefore attributed magnetic storms to recombination in the upper atmosphere of electrons and ions ejected as ionized clouds of neutral charge from the sun in eruptive prominences and propelled by light-pressure.

The effect of radiation pressure on gaseous particles in solar and stellar atmospheres has also been studied by Saha, Milne, Johnson, Sur, Chapman, S. R. Pike, and others. Milne's paper "On the Possibility of the Emission of High-speed Atoms from the Sun and Stars"³

¹ Pringsheim, *Physik der Sonne*, p. 225, 1910; Strutt, *Monthly Notices of the Royal Astronomical Society*, **57**, 59, 1916.

² Sur, *Astrophysical Journal*, **63**, 111, 1926.

³ *Monthly Notices of the Royal Astronomical Society*, **86**, 459, 1926.

is of special importance in its bearing on solar eruptions of the type described in the present article. His principal conclusions in this connection are as follows:

1. An atom which, due to some cause or other, begins to move outward from the sun with an appreciable velocity will begin to absorb in the violet wing of the absorption line corresponding to the same atom at rest, owing to the Doppler effect. It will therefore be exposed to more intense radiation. If it was originally a high-level atom in equilibrium under radiation-pressure and gravity, radiation-pressure will now exceed gravity, and the atom will be accelerated outwards. It will therefore move still further out into the wing, where it will be exposed to still more intense radiation, and so on, until it eventually "climbs out of" its absorption line and becomes exposed to the undiminished continuous spectrum.

2. The atom will ultimately acquire a limiting velocity, in virtue of the weakening of the radiation under the inverse square law. A limiting velocity may also be acquired in virtue of the atom being "trapped" by an adjacent absorption line.

3. For atoms projected from the sun in this way, from absorption lines of an intensity ratio of the order of $1/9$, the limiting velocity is of the order of 1.6×10^8 cms. sec.⁻¹ (1600 kms. sec.⁻¹). The velocity will be about the same for light atoms (e.g. *H*, *He*) and for heavy atoms (e.g. *Ca*⁺).

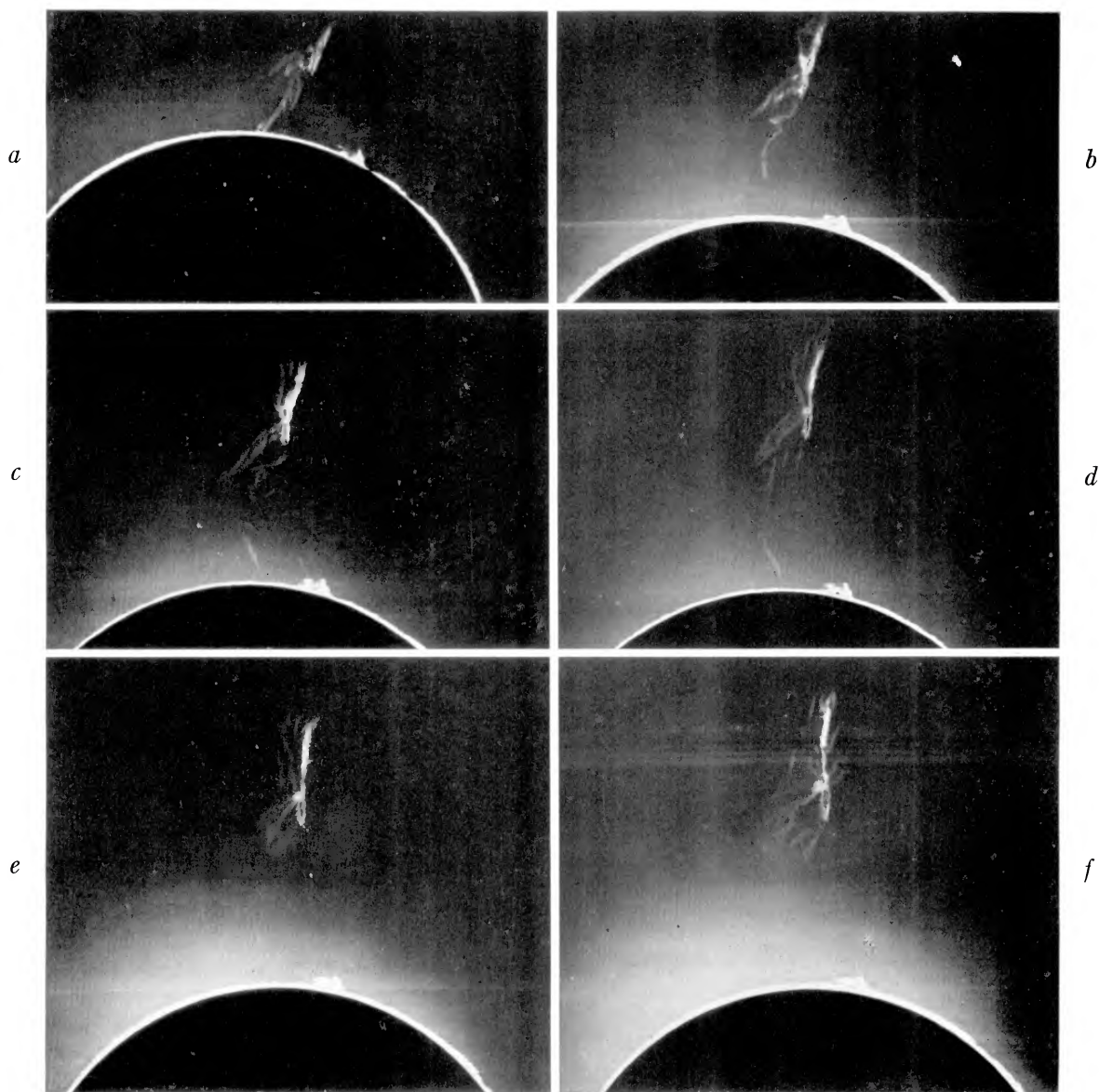
6. Particles projected in this way from the sun may be the cause of aurorae and magnetic storms. Comparison is made with Lindemann's theory. On the present theory the particles arrive with greater velocities, and may be much heavier, than on Lindemann's theory.

7. Use is made of Blackett's observations of the collisions of α -particles with argon atoms to estimate the air-range of *Ca*⁺ atoms (same atomic weight as argon) moving at 1.6×10^8 cms. sec.⁻¹. The equivalent air-range at N.T.P. is about 0.15 cm., which would be just about sufficient for them to penetrate the earth's atmosphere to the 100 kms. level, the observed lower level of aurorae.

8. Atoms may be projected neutral or ionised. Neutral atoms may become ionised and form neutral clouds, as in Lindemann's theory. Ionised (positively charged) atoms will be followed by an equal number of electrons, but the electrons will not be subject to appreciable radiation-pressure and will probably lag behind. Hence the cloud (if the projected particles are numerous enough to form such) will have a positively charged head and a negatively charged tail.

9. The phenomenon of accelerated escape will only occur if the atoms are not numerous enough to give rise to an absorption sufficient to "carry their absorption line with them." Random accelerated escape is possible at any time from any portion of the sun's surface, but escape is more probable from disturbed areas.

PLATE VIII



Eruptive prominence photographed at Kodaikanal November 19, 1928: *a*, 7^h52^m; *b*, 8^h35^m; *c*, 8^h45^m; *d*, 8^h52^m; *e*, 8^h58^m; *f*, 9^h3^m, I.S.T. Outward velocity 60 to 70 km/sec. in lower parts of prominence, 100 to 170 km/sec. in highest parts. Velocity increased with time, reaching 229 km/sec. at top between *e* and *f*. Height in *f* 495,000 miles; cut off by clouds at maximum height of 567,000 miles.

Pike's valuable contributions to the subject, so sadly terminated by his early death, will be discussed in a later paper of this series on the motions of hydrogen near sun-spots. In the present connection his most important conclusion is that "the vertical instability, due to the Doppler effect, which was first pointed out by Milne, is found to have a horizontal counterpart. An atom moving upwards is accelerated horizontally, resulting in a rapid dispersal of upward-moving clouds."¹ This seems to be borne out by the eventual diffusion of many eruptive prominences, though there are occasional exceptions of the type represented by Royds's remarkable series of photographs reproduced in Plate VIII.² As Pike stated, a difficulty of the radiation-pressure theory is to account for the extremely rapid acceleration of quiescent dark flocculi which suddenly shoot upward at great velocity. A very striking case of this kind is that recently described by Newton (see p. 401).

S. Chapman, who has made extensive investigations on the passage of charged particles from the sun to the earth and the motion of a neutral ionized stream in the earth's magnetic field, believes some form of corpuscular theory to be promising, but considers that the difficulties of the problem have been only partly overcome. In a recent paper he has discussed the theory of Hulburt and Maris, which ascribes auroras and magnetic storms to the action of small temporary spots of very high temperature on the sun, from which blasts of ultra-violet light ionize the gases at high levels in the earth's atmosphere. The ions thus formed descend in spirals around the lines of force toward the northern or southern auroral zones.³ Chapman maintains that these terrestrial corpuscles, with a speed of about 10 km/sec., could not possibly penetrate the atmosphere to the observed lower level of the aurora.⁴ It may be added that the existence of these supposed intensely hot regions has not yet been demonstrated. They are not shown in Pettit's photographs of the sun made with ultra-violet light, where they presumably ought to

¹ "The Motion of Gases in the Sun's Atmosphere," *ibid.*, **88**, 3, 1927.

² "A Very High Prominence on 1928, November 19," *ibid.*, **89**, 255, 1929.

³ Hulburt, *Physical Review*, **34**, 1167, 1929.

⁴ "On Solar Ultra-Violet Radiation as the Cause of Aurorae and Magnetic Storms," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, **2**, 296, 1930.

appear, or by spectroscopic means, though Carrington's observations might perhaps have been a case of this kind.¹

Deslandres, who has published a number of papers in the *Comptes rendus* on the relationship between solar and terrestrial magnetic phenomena, summarizes his opinion regarding the source and nature of the charged particles as follows:

Tout se passe comme si le Soleil avait sous la surface une couche profonde qui tourne comme un corps solide; et cette couche quasi solide offre 24 volcans, variables comme les volcans terrestres, et uniformément répartis autour de l'axe de rotation, qui rejettent au dehors la matière électrisée des masses intérieures. Si l'on admet que les particules négatives ou positives de ces volcans ont des vitesses différentes et sont lancées surtout par des corps radioactifs, on explique bien les particularités de nos orages. De plus, le rayonnement corpusculaire de la couche profonde apparaît comme la cause première de tous les phénomènes (taches, facules, polarités magnétiques, etc.) observés sur le Soleil et ses dépendances.²

From an exhaustive discussion of the magnetic records covering the period 1906–1925, inclusive, Chree and Stagg arrived at the following conclusions:

The 27-day interval has been found to present itself in disturbance of any size, large or small. No certain difference has been found in the length of the interval, as between years of low and years of high sunspot latitude, or as between years of many and years of few sunspots. No certain departure has been found from 27.0 days in any type of years. There is an apparent tendency for the interval to be greater the larger the primary disturbance. But this is, at least partly, due to the tendency in very large disturbance to rise more quickly than it falls.

The secondary pulse following 27 days after large disturbance is due, in part, to an increase in the proportion of highly disturbed days, but it also owes a good deal to a diminution in the proportion of very quiet days. Similarly, the secondary pulse following 27 days after exceptional magnetic quietness is due, in part, to an increase in the proportion of very quiet days, but it also owes a good deal to the diminution in the proportion of very disturbed days.

The secondary pulse is better developed in years of few than in years of

¹ It seems very probable that any such ultra-violet outbursts, if they exist, will coincide in time and position with the calcium and hydrogen eruptions described in this paper. If so, the observed time interval between the solar and terrestrial effects should serve as another means of testing the theory of Hulburt and Maris.

² For a more complete statement of M. Deslandres' views see his paper entitled "Loi de distribution des orages magnétiques et de leurs éléments. Conséquences à en tirer sur la constitution du Soleil," *Comptes rendus*, 185, 626, 1927.

many sunspots, and better in years of low than in years of high spot latitude, but other causes helping or hindering its development seem to exist.

In some years there seems a decided tendency for the international quiet and disturbed days to form members of the same sequence. Supposing magnetic disturbance due to radiation of some kind from the sun, and the solar area effective on any one day to be a narrow zone, then some solar zones must retain their disturbed condition for many solar rotations, whilst others must be alternately much more disturbed than the average zone and much less.

No trace has been found of the existence of any disturbance interval which is a submultiple of 27 days, but there seems in all kinds of years a decided tendency for high disturbance to develop from 4 to 6 days after the occurrence of conspicuous quietness.¹

Greaves and Newton, who have since discussed this problem in a paper entitled "Large Magnetic Storms and Large Sunspots,"² reach the following conclusions:

A comparison between the large magnetic storms and large sunspots during the period 1874 to 1927 shows that individual storms and individual spots are associated with each other more often than can be ascribed to mere chance. The tendency to association appears to be greater for the very largest storms of all. It would seem that whatever solar activity is responsible for a magnetic storm, if it is sufficient to produce an unusually large storm, it will probably manifest itself as a large sunspot. But attention has been called to a case of a very large storm taking place at a time when only very moderate spots were visible.

No very definite evidence has been found of a tendency for these large storms to be followed by another magnetic disturbance after an interval of one solar rotation. The evidence available suggests that there may be a slight tendency for recurrence, but it is not very conclusive.

In a later paper they state:

It would thus appear that the recurrence characteristic is mainly a property of the storms of smaller range. The recurrence tendency has been used to ascribe magnetic storms to the action of radial streams proceeding from limited areas of the sun. The present investigation in no way contradicts this conclusion, but suggests an additional hypothesis, namely, that for the more intense storms the solar disturbance from which the stream is being ejected is in general short-lived, and does not survive a solar rotation in an appreciable number of cases.³

After giving the average areas of the largest sun-spots at the time of commencement of magnetic storms, they add:

¹ "Recurrence Phenomena in Terrestrial Magnetism," *Philosophical Transactions of the Royal Society of London*, A, 227, 61, 1927.

² *Monthly Notices of the Royal Astronomical Society*, 88, 567, 1928.

³ *Ibid.*, 89, 641, 1929.

On comparing the data in this table with the diagram, there is seen to be a marked antithesis between the tendency to recurrence and the tendency for the storms to be associated with spots. The paradox, however, is more apparent than real, as the occurrence of storms during spotless periods shows that the spots themselves are not the actual seat of origin of the streams responsible for the storms. All that can be said is that there is a tendency for the solar disturbances responsible for the larger storms to be accompanied by spots larger than the average, and once it has been granted that the disturbances are not identical with the spots, there seems to be no serious difficulty in assuming that the larger disturbances may subside comparatively quickly although an associated spot may persist. In one respect the two sets of data are supplementary, as they both seem to indicate that the storms are connected with a disturbance on a limited area of the sun's surface, the recurrence tendency suggesting this for the smaller storms, whereas the correlation with sunspot data points to the same conclusion in the case of the larger storms.

In considering the foregoing theories the following results of my observations may be of service:

1. Quiescent prominences observed or photographed with $H\alpha$ on the sun's disk as dark flocculi commonly lie upon a brighter background of hydrogen, which often appears as a narrow frame partially surrounding the absorbing gas. Good illustrations of this effect may be seen, for example, in several of the spectroheliograms reproduced in the first paper of this series.¹

2. The brighter eruptive flocculi, which develop suddenly, often as brilliant points, are frequently capped in a few minutes by dark hydrogen, changing rapidly in form. As Newton has remarked, these bright flocculi produce, in general, only a small displacement of the bright $H\alpha$ line, corresponding to a velocity of ascent of a few kilometers per second. The velocity of the absorbing gas usually exceeds that of the bright flocculi from which it appears to rise.

3. As shown in the second article of this series, the absorbing hydrogen, after a rapid ascent, may often be seen rapidly falling toward a sun-spot or even toward the photosphere away from a spot. The failure of the gas to escape from the sun may result from one or more causes, including the influence of the spot, the angle of dis-

¹ "The Spectroheliometer and Its Work," Part I, Plates XXI, XXII, XXIII, *Mt. Wilson Contr.*, No. 388; *Astrophysical Journal*, **70**, 265, 1929. See also "Visual Observations of the Solar Atmosphere," *Mt. Wilson Communication*, No. 97; *Proceedings of the National Academy of Sciences*, **12**, 224, 1926.

charge, and the tendency of the absorbing atoms when too numerous to "carry their absorption line with them."

Bright eruptions, due to increased radiation from lower levels, seem to offer the most promising means of escape from the sun. The observed acceleration of the radial velocity, if confirmed at the sun's limb by the accelerated rise of prominences, is in harmony with the demands of the radiation-pressure theory of Milne. The high velocities needed to escape completely from the sun may be attained at higher levels, where the gas is too faint to be visible.

Whatever the underlying cause of the eruptions, they are almost sure to be shown in their early stages by the spectrohelioscope, either as bright flocculi or as superposed dark flocculi moving at accelerated velocities.

INTERNATIONAL CO-OPERATION IN WORK WITH THE SPECTROHELIOSCOPE

If we could take the observations given in this paper at their face value, supported as they seem to be by theory, we might conclude that bright auroras and exceptional magnetic storms result from solar eruptions, which carry charged particles to the earth in periods ranging from about eighteen to thirty-eight hours. It must be remembered, however, that the actual beginning of very few such eruptions has been observed, so that the true time intervals are still very uncertain. Moreover, in some cases the terrestrial magnetic storms commenced before these particular eruptions were recorded, though other outbursts may have preceded them. We must also bear in mind that several eruptions have occurred near the center of the sun without producing magnetic storms and that many magnetic storms without known solar antecedents have been registered, even at periods of minimum sun-spot activity.

It is probable that some of these discrepancies are due to the angle at which the eruptive gases left the sun and the form of their subsequent trajectories, not to speak of their possible diffusion after the manner described by Pike. But satisfactory conclusions will be possible only when more continuous solar observations become available.

Anyone who has regularly watched the sun with a spectrohelio-

scope is aware how suddenly and unexpectedly a bright or dark eruption may appear on the disk. My own observations include scores of such eruptions, most of which were relatively small. Moreover, as already remarked, a dark flocculus which has remained almost unchanged for days may instantly quicken into life and move rapidly horizontally or vertically, or completely disappear within a few minutes. Any of these phenomena, though far more common near or within a large group of sun-spots, may also happen at other points on the disk. It is therefore obvious that our observational means have been very inadequate in the past, though much could be accomplished with existing spectroheliographs if it were feasible to take $H\alpha$ photographs at half-hour or shorter intervals throughout the day. Even then, the small number of active spectroheliographs, their irregular distribution in longitude, and the interruptions due to cloudy weather would render the total record incomplete, especially when contrasted with the continuous photographic registration of the three elements of terrestrial magnetism at many stations.

The suitability of the spectrohelioscope for the required observations and the possibility of constructing a complete and efficient outfit at small expense offer the best available means of keeping the solar atmosphere almost continuously under view. I am glad to say that twenty-five coelostat telescopes and spectrohelioscopes of the type described in the first article of this series have already been built or ordered for use at widely distributed stations, most of which are listed in Table I.

Two other spectrohelioscopes of the standard type, which have just been completed, will be erected at favorable sites, and several others are likely to be built for use elsewhere. A general scheme of co-operation for the detection of eruptions on the sun's disk, in which spectroheliographs may also take part, will be organized in harmony with the present co-operative work of the International Astronomical Union.

A simple device for transforming a spectrohelioscope into a spectroheliograph, which has been built and tested at my Solar Laboratory, will be described in a later article of the present series. I have also designed a very inexpensive spectroheliograph, which

can be employed as a useful auxiliary of the standard spectrohelioscope, especially when it is desired to photograph quickly the forms of rapidly changing eruptive phenomena. In slightly modified form this spectroheliograph can be used as an automatic recorder, giving calcium images of the sun at any desired time intervals throughout the day.

TABLE I
SPECTROHELIOSCOPES

Observatory	Place	Latitude	Longitude
Royal.....	Greenwich, England	+51° 29'	0 ^h 0 ^m
Solar Physics.....	Cambridge, England	+52 13	0 0
Federal.....	Zürich, Switzerland	+47 23	- 0 34
Astrophysical.....	Florence, Italy	+43 45	- 0 45
American College.....	Beirut, Syria	+33 54	- 2 22
Solar Physics.....	Kodaikanal, South India	+10 14	- 5 10
Department of Terrestrial Magnetism of the Carnegie Institution of Washington.....	Watherhoo, Australia	-30 18	- 7 44
National Institute of Astronomy.....	Nanking, China	+32 7	- 7 55
Commonwealth Solar Observatory.....	Canberra, Australia	-35 20	- 9 56
Dominion.....	Wellington, New Zealand	-41 17	-11 39
Apia.....	Apia, Samoa	-13 48	+11 27
Mount Wilson, Carnegie Institution of Washington.....	Mount Wilson, Calif.	+34 13	+ 7 52
Mount Wilson, Carnegie Institution of Washington.....	Pasadena, Calif.	+34 8	+ 7 52
Pomona College.....	Claremont, Calif.	+34 6	+ 7 51
University of South Dakota.....	Vermilion, S.D.	+42 42	+ 6 28
Yerkes.....	Williams Bay, Wis.	+42 34	+ 5 54
Adler Planetarium.....	Chicago, Ill.	+41 50	+ 5 51
Ohio State University.....	Columbus, Ohio	+40 0	+ 5 32
Department of Terrestrial Magnetism of the Carnegie Institution of Washington.....	Huancayo, Peru	-12 3	+ 5 1
Vassar College (Physical Laboratory).....	Poughkeepsie, N.Y.	+41 41	+ 4 56
Bell Telephone Laboratories.....	New York City, N.Y.*	+40 45	+ 4 56
Massachusetts Institute of Technology (Physical Laboratory).....	Cambridge, Mass.	+42 23	+ 4 44
Franklin Institute.....	Philadelphia, Pa.	+39 58	+ 5 1

* This instrument will probably be erected at a site several miles from the Bell Telephone Laboratories in New York City.

This paper may appropriately close with a suggestion regarding the desirability of retaining an open mind toward the many theories under consideration. No one who has devoted years of observation to the complex phenomena of the solar atmosphere is likely to under-rate the difficulty of the problem. Radiation pressure as presented by Milne seems to account for the support of Ca^+ vapor in the solar

atmosphere and its escape from the sun if the ionized atom is being accelerated, but the difficulties are greater with hydrogen, which in prominences reaches nearly to the height of calcium, though there are some differences in distribution. Moreover, Pettit, who made an extensive study of the subject at the Yerkes Observatory, does not believe that the gases in eruptive prominences rise with a constant acceleration. It is evident that much observational work, both visual and photographic, remains to be done in this field.

Many of the phenomena observed on the sun's disk with the spectroheliograph are also very puzzling. In the radiation-pressure theory a sun-spot should be a center of attraction for neighboring ascending gases, but its influence on those at great distances should be negligible, as Pike has pointed out. Dark arches of hydrogen, it is true, usually rise from bright hydrogen flocculi, but they also frequently descend at high velocity upon or toward bright flocculi or upon apparently normal regions of the photosphere away from spots. It is desirable, as Pike has suggested, to determine by searching for local magnetic fields whether invisible whirls exist at these apparent points of attraction. Such questions, with others to be mentioned in subsequent papers, will provide ample occupation for anyone equipped with the necessary instruments.

I wish to express my thanks to Messrs. Fox and Abetti, Ellerman, Nicholson, Royds, and D'Azambuja, whose photographs of eruptive phenomena are reproduced in this paper. My indebtedness to others who have supplied information has already been acknowledged in the text.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
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