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On the Ultraviolet Light Theory of Magnetic Storms

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The three notable solar flares observed in the western hemisphere in 1936 did not produce magnetic storms. It is inferred from terrestrial effects accompanying them that intense ultraviolet emission occurred at the same time. Study of the effects suggests that, when a flare of ultraviolet light increases the conductivity of the lower regions of the atmosphere, increased diurnal-variation currents flow. The current-systems necessary to produce magnetic storms are of an entirely different type—hence the observed effects do not support the ultraviolet light theory of magnetic storms.

IN a series of papers which have appeared in this journal E. O. Hulburt and H. B. Maris have proposed and developed a promising theory, attributing auroral phenomena and magnetic storms to flares of ultraviolet light from the sun, as a substitute for the earlier corpuscular theory which has encountered numerous difficulties. The theory, as first proposed by Hulburt,[1] suggested that aurorae are due to ions, formed in the upper fringe of the ionosphere in low and middle latitudes, which drift along the lines of magnetic force to lesser heights in polar regions and there excite the auroral light by collision with other molecules. Chapman,[2] in criticism of this preliminary paper, pointed out that the lines of magnetic force along which ions must drift to fall into polar regions pass many tens of thousands of kilometers above the earth's surface in equatorial and middle-latitude regions, at which heights the atmospheric density must be quite inappreciable.

Subsequently Maris and Hulburt[3] and Hulburt[4] met these objections and extended the theory to account for magnetic storms as well as aurorae, introducing the assumption that through collisions of the second kind, involving excited atoms, some of the atmospheric atoms are projected to the necessary heights. The number of atoms above the 450-km level was estimated as 10^{16} in a column one square centimeter in cross section. In this region 2×10^6 atoms per second were assumed to acquire velocities as great as 10 km per second. A sudden flare of ultraviolet light from the sun, persisting for about half an hour, was assumed to cause an increase in the ionization and in the number of high flying atoms, the number of long-free-path ions thus produced reaching 10^{16} in a unit column. These ions, through the crossed gravitational and magnetic fields in equatorial regions, would give rise to an eastward electric current producing the increase in the earth's horizontal magnetic field observed at the beginning of a magnetic storm, while electric currents induced in the earth would cause the greater decrease in the field observed during the main phase. Falling from their great heights into polar regions, the high flying ions would cause aurorae and produce certain magnetic effects through their diamagnetic action.

Chapman[5] in further criticism of the theory stated that the explanation offered for the second-phase variations of a magnetic storm was contrary to electromagnetic theory and called attention to the fact that the curves of magnetic variation in polar regions, which the theory had explained, were incorrectly drawn by the authors. Dissatisfaction with the original hypotheses was also expressed but not extensively discussed since the theory in the form offered appeared incapable of accounting for the observed facts.

Without altering the original hypotheses Hulburt[6] in another paper described other effects involved so that the magnetic variations produced in accord with the more highly developed aspect of the theory agreed closely with the

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[1] E. O. Hulburt, Phys. Rev. **31**, 1038 (1928).

[2] S. Chapman, Phys. Rev. **32**, 993 (1928).

[3] H. B. Maris and E. O. Hulburt, Phys. Rev. **33**, 412 (1929).

[4] E. O. Hulburt, Phys. Rev. **34**, 344 (1929).

[5] S. Chapman, Mon. Not. R. Astr. Soc., Geophys. Sup. 2, 296 (1930).

[6] E. O. Hulburt, Phys. Rev. **36**, 1560 (1930).

observed facts, rejecting the first assumption of diamagnetic action in polar regions which did not give variations of the correct sign.

Since all ideas concerning the extreme upper ionosphere are highly speculative, a satisfactory appraisal of the theory and the underlying hypotheses on theoretical grounds is difficult. Direct observation of the terrestrial-magnetic effects produced by a flare of ultraviolet light from the sun should furnish a suitable basis for judging the theory. During 1936 three notable occurrences of H-alpha brightening in the region of sunspots were observed in the western hemisphere, all of which were attended by marked magnetic effects and fade-outs of radio signals from the ionosphere. These H-alpha brightenings are considered the visible manifestations of solar disturbances which emit intense flares of ultraviolet light, the latter, through its ionizing effect, being responsible for the changes in the earth's magnetism and the radio phenomena.[7]

These solar flares seem to be exactly what are called for by the ultraviolet theory of magnetic storms. A detailed study of the magnetic effects associated with them clearly indicates that *they do not produce magnetic storms but result in a very special type of magnetic effect* different in nature from those occurring during magnetic storms. In a recent review of theories of magnetic variations and aurorae Hulburt[8] states that a world-wide magnetic storm began simultaneously with the notable outburst on the sun occurring at 16^h 46^m GMT on April 8, 1936. He further concludes "the simultaneity of incipience of radio fade-out, ionospheric change, magnetic disturbance, and solar eruption appear to offer detailed support of the ultraviolet theory," adding the reservation: "However, rather than to stress the agreement prematurely it is better to await the results of future experiment." On the contrary, detailed reports by observers state "the magnetic traces for the preceding and following days, April 7 and 8, Greenwich dates, were quite undisturbed"[9] and "no magnetic disturbance followed."[10] Most magnetic storms persist for a day or more.

Evidence that a world-wide magnetic storm did not begin at the time stated is supplied by Fig. 1, showing the magnetic traces at the time of the solar eruption at three widely separated observatories, Huancayo (Peru), Cheltenham (United States), and Watheroo (Australia), and Fig. 2, showing the minimum degree of disturbance which is called a magnetic storm at those stations. This demonstrates that no storm accompanied or followed the solar flare. The curves in Fig. 1, except for the feature immediately associated in time with the solar flare, are

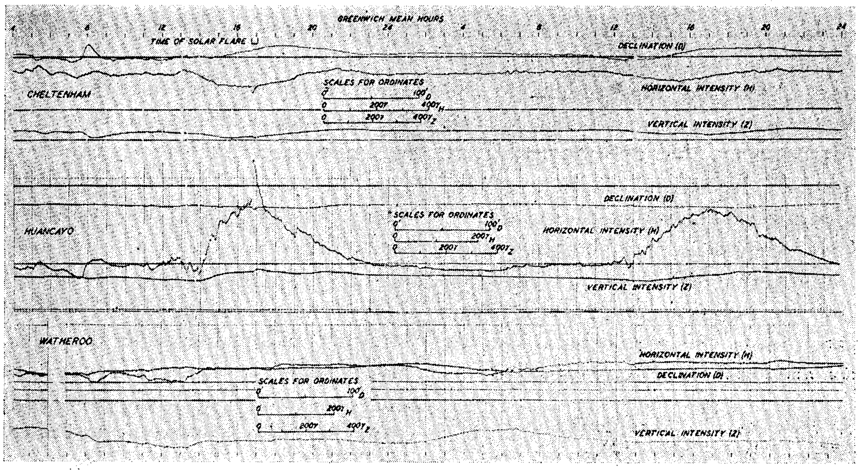

FIG. 1. Variations in earth's magnetic field before and after appearance of solar flare from 16^h 45^m to 17^h 03^m GMT, April 8, 1936.

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[7] J. A. Fleming, Terr. Mag. **41**, 404 (1936); A. G. McNish, Nature **139**, 244 (1937). Attention was first called to these phenomena by J. H. Dellinger, Phys. Rev. **48**, 705 (1935).

[8] E. O. Hulburt, Rev. Mod. Phys. **9**, 44 (1937).

[9] O. W. Torreson, W. E. Scott, and H. E. Stanton, Terr. Mag. **41**, 199 (1936).

[10] R. S. Richardson, Terr. Mag. **41**, 197 (1936).

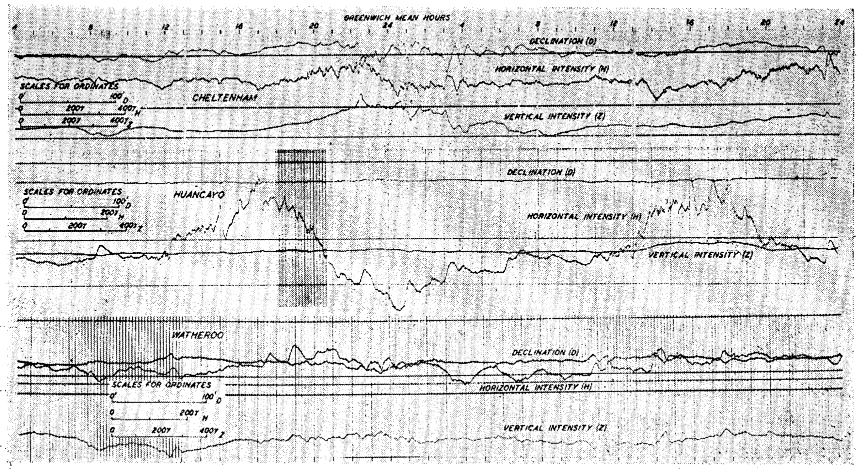

FIG. 2. Variations in earth's magnetic field during mild magnetic storm.

characteristic of what is observed at each observatory on an ordinary magnetically quiet day. No vestige of this solar-flare disturbance is present in the Watheroo record, indicating that the effect is not world-wide.

Careful examination of the records in Fig. 1 discloses that the earth's field was fluctuating slightly up to the time of occurrence of the flare but after its occurrence the earth's magnetic condition was even more quiescent. The records from 12 other magnetic observatories, scattered over the earth, have been examined. They reveal the same conditions. The pronounced but short-lived jump in the records, coincident with the flare, cannot be regarded as a magnetic storm, in the ordinary sense in which the term is used; nor is it world-wide, being confined to a region less than 90° from the subsolar point at time of occurrence. (Note absence of effect at Watheroo.)

Thus the statement in Hulburt's paper that a world-wide magnetic storm began at the time of fade-out is contradicted by the observed facts.

Plots of the average intensity of magnetic disturbance for each day at the Cheltenham, Honolulu, Huancayo, San Juan, Sitka, Tucson, and Watheroo magnetic observatories during the months of April, August, and November 1936 (Fig. 3) show that none of the three notable solar flares ~~of the~~ past year occurred during or immediately preceding a storm. Each occurred during a period of comparative quiescence and was immediately followed by fairly quiet days. Since all of these were exceptionally strong flares, one would have expected the magnetic disturbance to attain storm levels for the next two or three days in accord with the ultraviolet light theory.

The magnetic effects associated with the solar flares are found to be of a special type, distinct from the types accompanying magnetic storms. They consist of changes in the magnetic force at each station closely simulating in direction and magnitude the departures obtaining at the time of occurrence due to the regular diurnal variations of terrestrial magnetism which are strongly present even during the most quiet magnetic conditions. These ordinary diurnal variations, according to the Stewart-Schuster theory, are

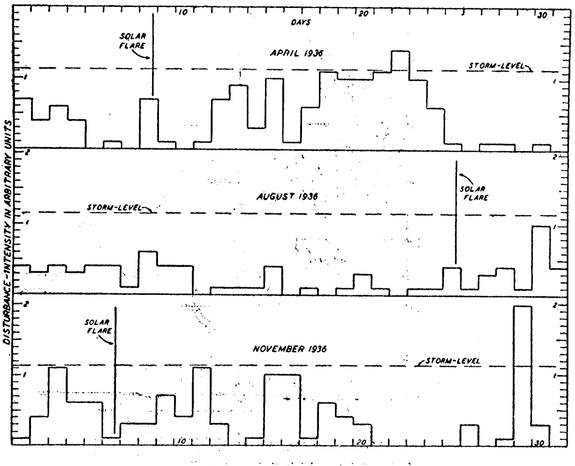

FIG. 3. Intensity magnetic disturbance, April, August, and November, 1936. based on numerical ratings from seven American-operated observatories.

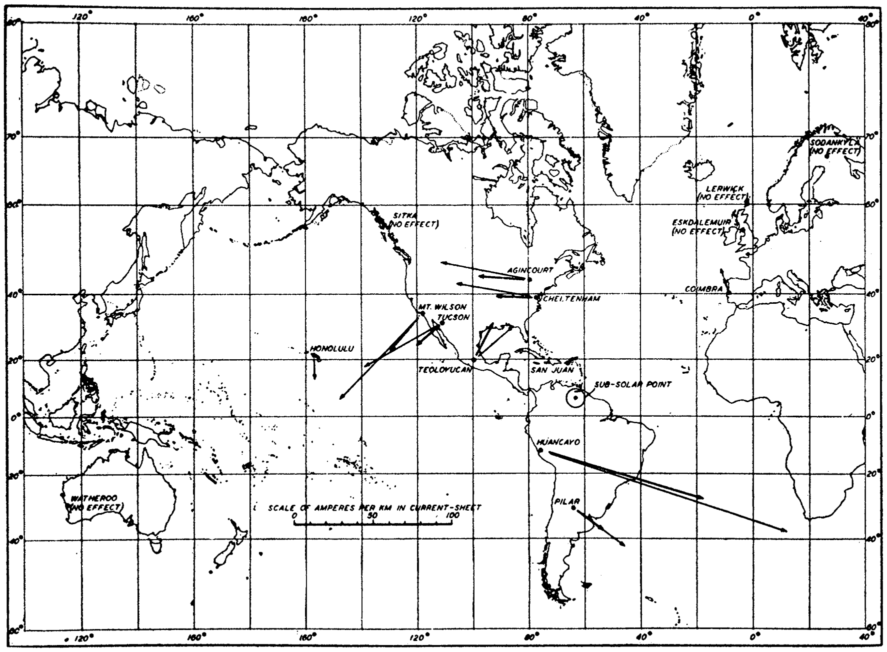

FIG. 4. Overhead currents necessary to produce magnetic changes observed at time of solar flare beginning 16ʰ 46ᵐ GMT, April 8, 1936 (heavy arrows), and normal diurnal-variation changes at same time (light arrows).

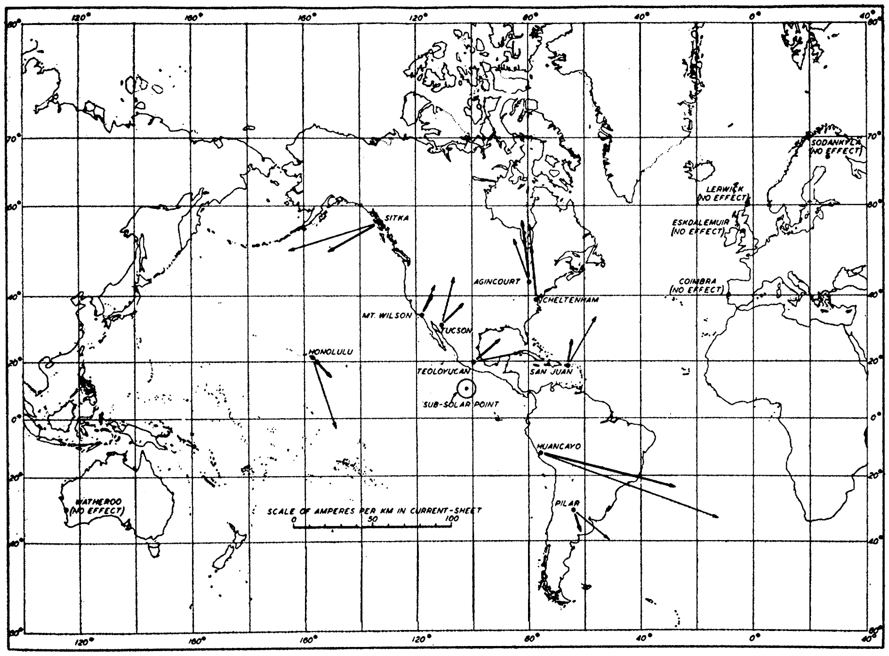

FIG. 5. Overhead currents necessary to produce magnetic changes observed at time of solar flare beginning 18ʰ 25ᵐ GMT, August 25, 1936 (heavy arrows), and normal diurnal-variation changes at same time (light arrows).

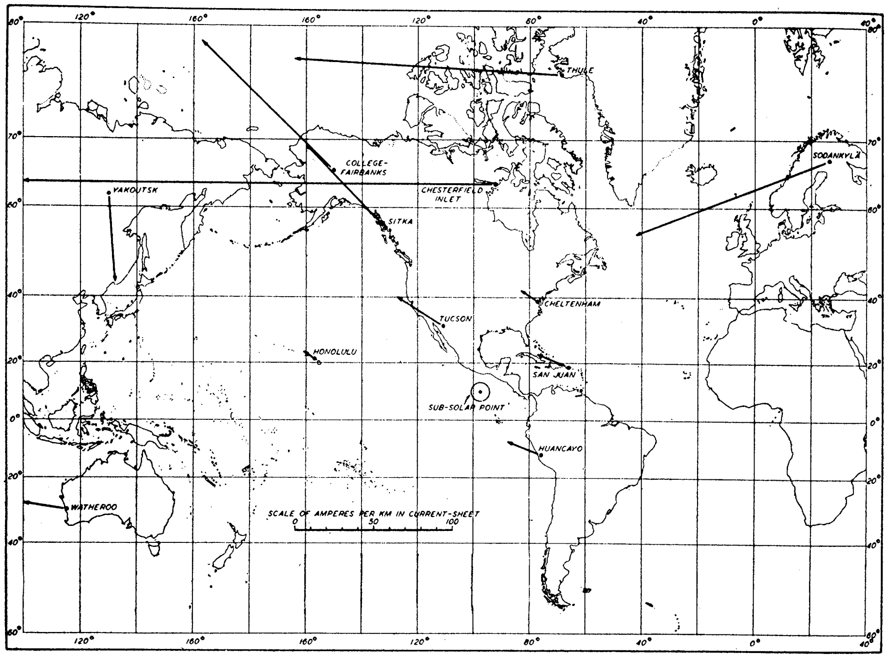

FIG. 6. Overhead currents necessary to produce magnetic changes observed at time of "bay"-type disturbance at $19^h\ 35^m$ GMT, April 16, 1933 (this type frequently occurs during magnetic storms).

caused by currents flowing in the atmosphere rendered conducting by solar ultraviolet light. A sudden increase in the ionizing radiation from the sun would cause an increase in these currents through the improved conductivity of the upper atmosphere. This view is supported by Figs. 4 and 5, showing the overhead currents necessary to produce the field changes associated with solar-flare disturbances (heavy arrows) and those necessary to produce the normal diurnal variation departures obtaining at the time (light arrows).[11] This increase of ionization occurs in the short-free-path region of the ionosphere and thus causes absorption of radio waves. It accounts for the observed fact that radio waves at frequencies which would ordinarily penetrate that region and be reflected back to earth from one or the other of the higher layers of ionization are not reflected during the disturbed period. Later, when the phenomenon has subsided, the return of reflections from those upper regions reveals that these layers have experienced no noticeable change.

On the other hand, the field changes occurring during a magnetic storm must involve a different mechanism. The overhead currents necessary to

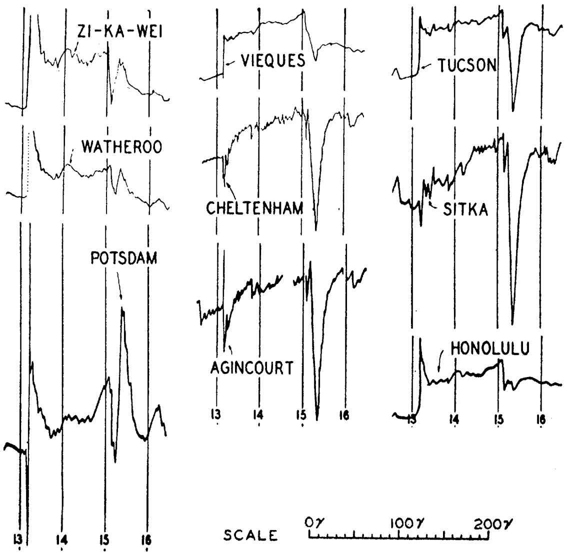

FIG. 7. World-wide sudden commencement of magnetic storm at $13^h\ 09^m$ GMT, May 13, 1921, horizontal-intensity changes.

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[11] A detailed study of the magnetic effects produced by these solar flares is under way at the Department of Terrestrial Magnetism, the results of which will be published shortly in *Terrestrial Magnetism and Atmospheric Electricity.*

produce the "bay"-type magnetic disturbance which frequently occurs during magnetic storms are shown in Fig. 6.[12] While the currents necessary to produce the solar-flare disturbance are greatest close to the subsolar point and do not flow beyond the twilight zone, those necessary to produce the bay-type disturbance are much more pronounced near the auroral zone (about 70° north) and extend over the entire earth. The form of the apparent system of circulation is obviously different in both cases.

Actual records of the sudden commencement of a magnetic storm at various observatories are shown in Fig. 7. This represents another type of magnetic disturbance quite different from the other two, but one which is characteristic of the beginning of a magnetic storm. The outstanding characteristic of this disturbance is its widespread manifestation, in sharp contrast to the circumscribed manifestation of a solar-flare disturbance. Obviously, the mechanism which gives rise to the sudden commencement of a magnetic storm must be quite different from that which operates when a sudden flare of ultraviolet light from the sun impinges on the earth's atmosphere.

Acknowledgment.—The writer expresses his appreciation to various individuals and organizations which have made available to him the special data necessary for this study, and in particular to Dr. J. A. Fleming, Director of Carnegie Institution's Department of Terrestrial Magnetism, whose recognition of the importance of these phenomena has caused him to encourage and support the investigation of which this is a part.

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[12] A. G. McNish, Trans. Am. Geophys. Union, 17th annual meeting, 166 (1936).

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The Far Infrared Spectrum of Water Vapor

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The rotation spectrum of water vapor has been measured with high dispersion from 18μ to 75μ. The spectrometer employed echelette gratings and higher spectral orders were successfully removed through the use of filters and selective reflection. The positions of single lines were determined with an accuracy of about 0.05 cm^{-1} throughout the entire region while neighboring lines as close together as 0.5 cm^{-1} could be separated and measured. The analysis of the spectrum was accomplished in the following manner. From the values of the moments of inertia found by Mecke the energy levels were calculated from the asymmetric rotator equations. However, these computed levels are often far from the actual energy levels due to the presence of a large correction arising out of the centrifugal force stretching of the molecule. An estimate of this correction, which amounted in some cases to over 200 cm^{-1}, was made, thus furnishing energy levels with which to begin the analysis. The intensities of the rotation lines were calculated by using as an approximation the symmetric rotator amplitudes. By comparing the expected spectrum with the observed spectrum it was then possible to identify the lines and through them to determine the actual energy levels of the water vapor molecule. Combination relations as well as the formation of analytic series from analogous lines, served as important checks on the identifications. Through these methods the rotational energy levels of the water molecule have been found up to and including the group of $J=11$ with an accuracy around 0.1 cm^{-1}. The highest level determined, possesses an energy of over 3200 cm^{-1}, while all the rotational levels with energies less than 2000 cm^{-1} have been obtained. Finally all the allowed transitions together with their intensities are calculated and these are plotted directly above the observed spectrum. The agreement is remarkably good. All the essential features of the spectrum and indeed most of the finer details are correctly reproduced.

I. Experimental

The present investigation covers the spectral region extending from 18μ to 75μ, thus overlapping somewhat the work of Wright and Randall[1] which began at 60μ. This earlier work demonstrated that the equipment used was capable of resolving and measuring the rotation spectrum of water with a completeness and accuracy not hitherto attained in this region of the spectrum. It was, however, so responsive to outside disturbances that much time was lost waiting for favorable conditions, often to be

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[1] Norman Wright and H. M. Randall, Phys. Rev. **44**, 39 (1933).

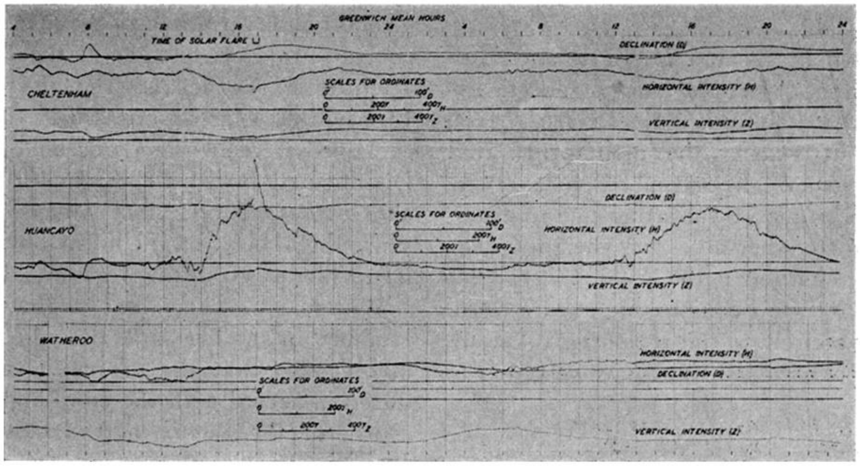
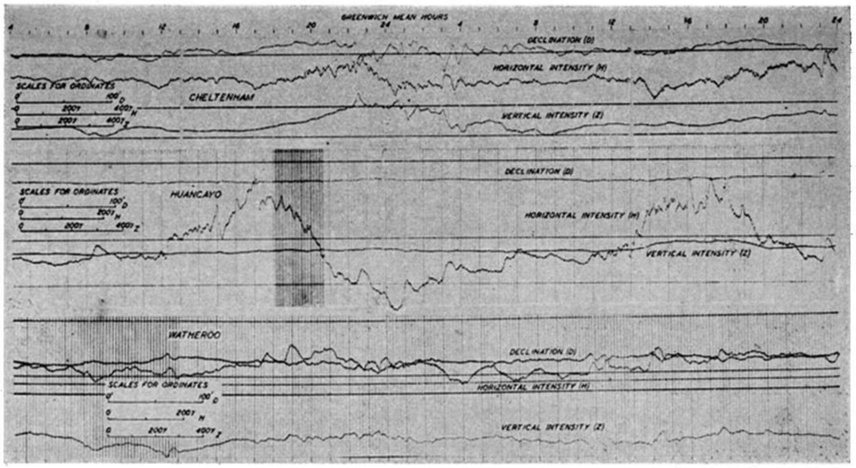


FIG. 1. Variations in earth's magnetic field before and after appearance of solar flare from $16^h\,45^m$ to $17^h\,03^m$ GMT, April 8, 1936.



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