THE PHYSICAL THEORY OF THE EARTH'S MAGNETIC AND ELECTRIC PHENOMENA—No. II.

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a. Introductory Note.

b. On the Non-Simultaneity of Magnetic Disturbances.

a. INTRODUCTORY NOTE.

15. In the "Foreword" to No. I, one chief purpose of these papers was explained, viz., to *elicit discussion*, the concluding statement being:

As these inquiries progress I shall be exceedingly grateful for any notification of errors in reasoning or misapplication of laboratory experimental facts, as well as for suggestions regarding points at issue or methods of attack. It is only by the combined effort of many minds that any distinct advance can be made in any field today. Full credit will be given, of course, for any hints received.

As No. II was being prepared, a letter was received from Adolf Schmidt stating that he would send, within a few days, a paper giving the conclusions of his own researches on magnetic storms. Accordingly the September issue was held back three weeks pending arrival of Schmidt's paper; his diagrams arrived, but not the expected article. With the desire of publishing the views of others alongside those of mine, No. II was postponed and the September issue appeared without it. On November 2 a letter was received from Schmidt stating that, owing to pressure of his various duties, he must defer sending his article.

Perhaps it ought to be explained that Schmidt's recent investigations on magnetic disturbances have been made in co-operation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. It was thought best to leave to him the investigation of magnetic disturbances so as to permit my whole time to be given to the problems of the magnetic survey of the globe, the burdens of which can be but little appreciated. Pending the conclusion of Schmidt's labors, it was decided to defer completion of the discussion of the magnetic disturbance of May 8, 1902, which, as may be recalled, occurred remarkably coincident with the eruption of Mont Pelé. The Department had in its archives the most complete data relating to this disturbance, the material embracing nearly every magnetic observatory over the whole globe. But, in the meanwhile, a discussion of this disturbance was undertaken by Chree, the results of whose investigation did not come to my attention until the receipt of a printed copy of his presidential

address, February 12, 1909, before the London Physical Society—almost a year after its delivery. The 1909 volume of the Antarctic Expedition containing the discussion in full was received about the same time. Chree's discussion was based upon but five stations against about twenty-five available ones in my possession. Hence, although very hard pressed at the time with onerous duties of various kinds, I undertook to push to partial completion, at least, the investigation of the "Mont Pelé Disturbance."

16. While engaged on the study of this interesting disturbance of May 8, 1902, I was led to the question *as to the strict simultaneity of magnetic disturbances*, and so looked up the literature. I was gradually led to conclusions at variance with some of those in Birkeland's book (Vol. I, The Norwegian Aurora Polaris Expedition, 1902-03). Up to that time there had appeared in print only favorable notices of the Birkeland-Störmer theory of magnetic disturbances. The most elaborate review was that of Nippoldt in the "Beiträge zur Geophysik," v. X, No. 2, pp. 96-100, published in December, 1909. Though familiar with Schmidt's theory of magnetic disturbances, which had been attacked by Birkeland, he had nothing to say in defense, but instead endorsed Birkeland's work in every respect; it was natural to conclude, therefore, that Schmidt had abandoned his theory of wandering vortices. (Met. ZS., 1899, p. 385.)

This was the status of matters when the various papers on magnetic disturbances published by me during the present year were in progress. After the adverse conclusions on the portions of Birkeland's cathode theory in question had been reached, there was received Chree's address before the Royal Institution last spring, in which, proceeding on different lines from mine, he had also reached some unfavorable opinions of this theory.

17. Chree has recently made some criticisms of my own papers, the only information regarding which I have at present are abstracts in *Nature*.

If he is reported correctly, then it would seem that he has not wholly understood me. Could Nos. II and III have appeared, as planned, he would have found that some of the points raised by him have already been covered. In view of the renewed interest being shown now in magnetic storms, it is to be regretted that Mr. Faris's article on the most interesting and suggestive magnetic perturbations thus far come to light—those of December 29 to 31, 1908—and No. III, containing the results of the mathematical analysis of this, as well as of other disturbances, must be deferred for want of space to the next issue (March, 1911). Chree devotes a large part of his criticisms in an attempt to break down the correctness of Faris's data. I think Chree will soon find that he is wrong; in the meantime, he is referred to the instructive exhibit as to the accuracy of time scalings, following the methods of the Coast and Geodetic Survey magnetic observatories given by Faris on pp. 213-214 of this issue.

b. ON THE NON-SIMULTANEITY OF MAGNETIC DISTURBANCES.

18. The chief physical fact that I desired to emphasize as new in my paper on the "Beginning and Propagation of Magnetic Disturbances" (*Terr. Mag.*, XV, 1910, p. 9) was that, contrary to previous belief, magnetic storms began at measurably different times at distant points of the Earth's surface—in brief, that *magnetic disturbances do not, in general, begin at the same absolute instant over the whole Earth.* Mr. R. L. Faris next took up the question and showed, with the aid of fifteen cases of sudden disturbances between July 29, 1906, and Sept. 25, 1909, that, even over the limited region embraced by the five magnetic observatories, Porto Rico, Cheltenham (Maryland), Baldwin (Kansas), Sitka (Alaska), and Honolulu, the times of beginning were appreciably different. Besides that, he verified a fact already previously found by van Bemmelen that *for the same station the time of beginning of a disturbance may be measurably different for the three registered elements*—the declination, the horizontal and the vertical intensity.

The opinion generally held previous to the researches of Faris and of myself is well shown by the following quotation from Nippoldt's "Erdmagnetismus, Erdstrom und Polarlicht," 1903, p. 69:

Wie ein Ungewitter die träge Ruhe eines heissen Sommertages plötzlich in ihr Gegenteil, in Sturm und Regenschauer verwandelt, so bricht auch die magnetische Störung oft plötzlich und ohne jedes Anzeichen aus und zwingt die Nadel des Variometers zu lebhaftester Bewegung. Man spricht daher wohl auch von einem "magnetischen Gewitter." Der Unterschied gegen die meteorologischen ist aber der, dass die Eintrittszeit für das ganze Gebiet, in dem die Störung auftritt, nicht messbar verschieden ist; wahrscheinlich ist sie dieselbe. Man hat daher solche Ausbruchszeiten und ähnliche scharf bestimmte Phasen einer Störung dazu benutzen wollen, den Unterschied der geographischen Länge zweier Orte zu bestimmen. Das gestörte Gebiet ist oft so gross, dass es die ganze Erde umfasst.

It will be seen that Nippoldt distinctly states that the times of beginning of a magnetic disturbance over the entire region involved "are not measurably different and probably the same everywhere," and he refers to the proposed use accordingly of magnetic disturbances for determining longitude.

In *Nature*, May 19, 1910, p. 355, Chree says: "These sudden commencements of storms are not unusual, and seem to occur simultaneously all over the earth."

19. Let us begin with the very disturbance—the one of May 8, 1902—which first led to the inquiry. The reader who wishes to get an idea of the character of the disturbance may be referred to the various curves, Figures 1 and 2 in *Terr. Mag.*, XV, p. 14. The times of beginning for 25 observatories were scaled in my office by two of my assistants several years ago, *before* any question arose regarding non-simultaneity; they will be found in Table I, p. 13, of this volume. Quoting from that paper (p. 14):

In order to minimize the effect of the inevitable uncertainties in the time determinations, the results were summarized in the following three groups:

Group I represents the average of all European observatories (eight for horizontal intensity and eleven for declination, stations Nos. 1-11), Group II, the average of eight observatories situated in the Indian Ocean, Asia, Australia, and New Zealand (stations 12 to 19), and Group III is the average of the six observatories located in the Hawaiian Islands, North America, and Staten Island in the South Atlantic Ocean (stations 20 to 25). In forming the weighted mean time, in the last column of Table II, double weight has been given to the time derived from the horizontal intensity magnetograms for the reason already stated.

TABLE II. *Greenwich mean civil times of magnetic disturbance May 8 1902, arranged in three groups.*

Group	Average		Disturbance began Greenwich Mean Civil Time		
	Latitude	Longitude	Hor. Int. H	Decl'n D	Weighted Mean
I	°	°	h m	h m	h m
II	51.3 N	9.7 E	11 58.24	11 57.89	11 58.12
III	1.7 N	111.4 E	58.72	59.13	58.86
	25.3 N	258.1 E	60.31	59 56	60.06
Mean	26.1 N	126.4 E	11 59.09	11 58.86	11 59.01

Looking over these figures, it is seen that for both elements (H and D), the time of beginning increases with increasing east longitude. Letting x = time it took the disturbance to pass over 90 equatorial degrees of longitude, *i. e.*, over a quadrant of the Earth, we find for the value, by least squares, 0.886^m; hence, to travel around the Earth completely it would take the disturbance 4 times 0.886 = 3.55^m, or about three and one-half minutes—a measurable interval especially by taking the mean, as was done, of several stations. Practically the same result is reached by treating the H and D times separately instead of combining into a weighted mean.

The times as obtained from the vertical component Z were not considered in above table on account of the greater difficulty in accurate scaling of time as compared with D and H ; there were but few of these any way. The aim was to have a recorded time for each group, to which, as far as circumstances permitted one to judge, about the same weight could be attached.

Since this table was published, slightly different combinations have been formed and a separation of stations for Northern and Southern Hemispheres was made; however, the general result is the same, the time required to pass over a quadrant being such that, if the disturbance continued around the whole earth at the same rate, it would take about 4 minutes.

[Instead of defining x as the time required for an arc embracing 90 equatorial degrees of longitude, it would doubtless have been better to have said an arc covering one fourth of a great circle. I have provisionally used this quantity as a convenient way of expressing, according to a common measure, the resulting time differences in units on the order of the possible error of the scalings. That I do not suppose the actual progression of the cause of the disturbance to be overhead in the plane of the geographic equator, as Chree infers, must be clear from my statements on pp. 20, 25, and from my method of analysis (*Terr. Mag.*, v. XV, p. 21). More will be said on this point in No. III. In the following paragraphs the plus sign is given to x when the times increase going east and a minus sign for progression of the times westward.]

20. Next was considered the magnetic disturbance of Jan. 26, 1903, for which Birkeland had scaled the times himself, not only for the point of beginning (1), but also for 5 other characteristic points (2 to 6). In the combinations made in the previous paper (pp. 17, 18), it was overlooked that the order in which Birkeland had tabulated the 17 stations embraced was not strictly according to increasing east longitude. Re-arranging and making two groups, viz., W (7 stations in the Northern and Western Hemispheres) and E (8 stations in the Northern and Eastern Hemispheres) Table III results. After each time is given the number, n , of available stations for the particular point considered. [While this article is passing through the press, I am enabled to make further improvements with the aid of some corrections on Birkeland's scalings for point (1), made by O. Krogness, *Nature*, Dec. 8, 1910, p. 171.]

Note the persistence in sign of the differences, $E-W$, in spite of the fact that different combinations of observatories occur in general, for each of the 6 points considered. Birkeland does not

state from what element (*D*, *H* or *Z*) he got his time; this, as has been shown by Faris (*Terr. Mag.*, xv, p. 104), is a very important matter.

21. Now, as to the examination made by Ellis (*Proc. Roy. Soc.*, Vol. 52, p. 191); 17 cases of abruptly beginning magnetic storms during the period April 16, 1882 to July 17, 1889, were embraced in his investigation. Table IV is a reproduction of his Table I, only the last three columns having been added by me. The first half tabulates the time for 8 observatories, next the mean of all for each disturbance is formed; the second half gives the difference

TABLE III. *Greenwich mean civil times for magnetic disturbance, January 26, 1903.*

Group	Average Latitude	Average Longitude	Average Greenwich Mean Civil Time for Point											
			1		2		3		4		5		6	
			t	n	t	n	t	n	t	n	t	n	t	n
W	40.63° N	59.77° W	h m 8 52.62	5	h m 10 52.53	3	h m 11 30.58	4	h m 12 32.12	4	h m 13 53.10	3	h m 14 17.28	4
E	44.70° N	48.98° E	53.05	4	52.90	4	31.32	6	32.12	8	53.56	8	18.20	8
E-W			+0.43		+0.37		+0.74		0.00		+0.46		+0.92	

$$\text{Mean of all } (t_e - t_w) = +0.58^m$$

$$\text{Arc of great circle connecting E and W} = 73.5^\circ$$

$$x = \text{time required to pass over a quadrant} = 0.58 \times \frac{90}{73.5} = +0.71^m$$

$$T = \text{time required to pass over a great circle} = +2.8^m$$

or deviation found by subtracting the mean time of 8 stations from the times for the individual stations. Even Ellis calls attention to the remarkable persistence in the signs of the deviations which, in general, prevail. Simply looking casually over the deviations, the impression is obtained that they are subject to some systematic run. To bring this fact out more clearly, the columns *W* and *E* were formed, which give, respectively, the mean deviations for the first four and the second four observatories. A minus deviation would mean that the time for any one station, or combination of stations, is less than the mean of all stations. The last column gives the difference *E-W*, i. e., $t_e - t_w$. Note that in but 3 instances out of 17, covering 7 years of observation, the sign of *E-W* is negative; in other words, the average time of beginning of a sudden

TABLE IV.—Time of commencement of magnetic movement at different places compared.

No. for Reference.	Observed time of commencement of magnetic movement at the different places reduced to Greenwich civil time										Daily mean of times										Deviation of time at each place from the mean										Mean deviation		E. W.				
	Day and hour		Toronto.		Greenwich.		Pawlofsk.		Mauritius.		Bombay.		Batavia.		Zi-ka-wel.		Melbourne.		Toronto.		Greenwich.		Pawlofsk.		Mauritius.		Bombay.		Batavia.		Zi-ka-wel.			Melbourne.		Mean deviation	
																																				Mean T. G. P. M.	B. Ba. Z. Mc
1	1882.	Apr.	d 16	h 23	m 33.6	m 34.0	m 33.1	m 35.8	m 35.0	m 37.0	m 31.3	m 38.4	m 34.8	-1.2	-0.8	-1.7	+1.0	+0.2	+2.2	-3.5	+3.6	-0.68	+0.62	-1.36	-0.68	+0.62	-1.36	-0.68	+0.62	-1.36	-0.68	+0.62	-1.36	-0.68	+0.62	-1.36	
2	1882.	Apr.	d 20	h 23	m 32.6	m 35.7	m 35.0	m 36.0	m 36.7	m 39.7	m 33.3	m 33.4	m 35.2	-2.6	+0.5	-0.2	+0.8	+1.5	+4.5	-2.9	-1.8	-0.38	+0.32	-0.77	-0.38	+0.32	-0.77	-0.38	+0.32	-0.77	-0.38	+0.32	-0.77	-0.38	+0.32	-0.77	
3	1882.	June	d 15	h 15	m 45.6	m 47.7	m 48.2	m 49.8	m 49.4	m 48.7	m 45.3	m 50.0	m 48.2	-2.3	-0.8	-0.8	-0.1	-0.2	+4.8	-3.6	+1.2	-0.60	+0.55	-1.20	-0.60	+0.55	-1.20	-0.60	+0.55	-1.20	-0.60	+0.55	-1.20	-0.60	+0.55	-1.20	
4	1882.	Aug.	d 4	h 15	m 45.6	m 48.7	m 48.2	m 49.8	m 49.4	m 48.7	m 45.3	m 50.0	m 48.2	-2.6	+0.5	-0.8	+1.6	+1.2	+0.8	-2.9	+1.8	-0.38	+0.32	-0.77	-0.38	+0.32	-0.77	-0.38	+0.32	-0.77	-0.38	+0.32	-0.77	-0.38	+0.32	-0.77	
5	1882.	Sept.	d 12	h 2	m 53.5	m 54.9	m 55.8	m 56.8	m 57.2	m 56.0	m 55.1	m 51.5	m 51.5	-0.6	-0.7	-1.0	-0.4	-0.5	+2.5	-4.6	+4.9	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	
6	1882.	Oct.	d 2	h 9	m 39.6	m 39.5	m 39.2	m 39.8	m 39.7	m 42.7	m 35.6	m 45.1	m 40.2	-0.6	-0.7	-1.0	-0.4	-0.5	+2.5	-4.6	+4.9	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	
7	1883.	Nov.	d 17	h 10	m 17.6	m 20.0	m 20.2	m 21.1	m 22.0	m 20.7	m 21.3	m 25.1	m 21.2	-1.2	-0.1	-1.0	-0.4	-0.5	+2.5	-4.6	+4.9	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	
8	1883.	Feb.	d 24	h 13	m 40.6	m 41.7	m 42.2	m 43.8	m 40.7	m 44.0	m 38.3	m 45.1	m 41.8	-1.2	-0.1	-1.0	-0.4	-0.5	+2.5	-4.6	+4.9	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	-0.68	+0.58	-1.26	
9	1883.	Apr.	d 3	h 9	m 0.6	m 1.0	m 1.2	m 0.2	m 1.4	m 4.7	m 1.2	m 0.1	m 0.9	-0.3	+0.1	+0.3	-1.1	+0.5	+3.8	-2.1	-0.8	-0.25	+0.35	-0.64	-0.25	+0.35	-0.64	-0.25	+0.35	-0.64	-0.25	+0.35	-0.64	-0.25	+0.35	-0.64	
10	1883.	July	d 29	h 23	m 45.6	m 46.5	m 47.2	m 46.1	m 44.7	m 48.7	m 41.0	m 55.1	m 47.0	-0.3	+0.5	-0.2	-0.9	-2.3	+1.7	-5.2	+8.1	-0.65	+0.58	-1.26	-0.65	+0.58	-1.26	-0.65	+0.58	-1.26	-0.65	+0.58	-1.26	-0.65	+0.58	-1.26	
11	1884.	Sept.	d 16	h 2	m 43.6	m 42.0	m 44.1	m 44.8	m 44.0	m 46.6	m 41.0	m 45.1	m 43.9	-0.3	-1.9	+0.2	+0.9	+0.1	+2.8	-2.9	+1.2	-0.38	+0.30	-0.55	-0.38	+0.30	-0.55	-0.38	+0.30	-0.55	-0.38	+0.30	-0.55	-0.38	+0.30	-0.55	
12	1884.	July	d 2	h 19	m 14.5	m 15.3	m 16.1	m 16.8	m 16.4	m 18.7	m 15.3	m 15.1	m 16.0	-1.5	-0.7	+1.1	+0.8	+0.4	+2.7	-0.7	-0.9	-0.62	+0.62	-1.22	-0.62	+0.62	-1.22	-0.62	+0.62	-1.22	-0.62	+0.62	-1.22	-0.62	+0.62	-1.22	
13	1885.	June	d 24	h 22	m 30.6	m 31.0	m 31.1	m 31.8	m 30.4	m 32.7	m 27.3	m 35.1	m 31.0	-2.4	-0.7	+1.1	-0.5	+0.4	+3.7	-0.7	-0.9	-0.20	+0.08	-1.22	-0.20	+0.08	-1.22	-0.20	+0.08	-1.22	-0.20	+0.08	-1.22	-0.20	+0.08	-1.22	
14	1885.	June	d 2	h 21	m 48.6	m 50.3	m 52.1	m 50.5	m 51.4	m 54.7	m 50.3	m 50.1	m 51.0	-0.7	-0.3	-0.2	+0.5	-0.9	+1.4	-4.0	+3.8	-0.68	+0.68	-1.36	-0.68	+0.68	-1.36	-0.68	+0.68	-1.36	-0.68	+0.68	-1.36	-0.68	+0.68	-1.36	
15	1886.	Mar.	d 30	h 8	m 21.6	m 22.7	m 20.1	m 22.5	m 21.7	m 24.7	m 20.8	m 25.1	m 22.4	-0.8	+0.3	-2.3	-0.1	-0.7	+2.3	-3.4	+0.4	-0.35	+0.42	-0.73	-0.35	+0.42	-0.73	-0.35	+0.42	-0.73	-0.35	+0.42	-0.73	-0.35	+0.42	-0.73	
16	1888.	Oct.	d 30	h 19	m 43.6	m 44.7	m 48.1	m 43.8	m 45.0	m 45.7	m 41.3	m 45.1	m 44.7	-1.1	0.0	+3.4	-0.9	+0.3	+1.0	-3.4	+0.4	-0.35	+0.42	-0.73	-0.35	+0.42	-0.73	-0.35	+0.42	-0.73	-0.35	+0.42	-0.73	-0.35	+0.42	-0.73	
17	1889.	July	d 17	h 4	m 47.6	m 50.0	m 50.1	m 49.8	m 49.0	m 52.7	m 47.4	m 45.1	m 49.0	-1.4	+1.0	+1.1	+0.8	0.0	+3.7	-1.6	-3.9	-0.45	+0.38	-0.88	-0.45	+0.38	-0.88	-0.45	+0.38	-0.88	-0.45	+0.38	-0.88	-0.45	+0.38	-0.88	

disturbance as deduced from an easterly group of stations is in the majority of cases greater than that for a westerly group.

$$\begin{aligned}
 &\text{Average plus } (t_e - t_w) = \overset{m}{+0.95}; 14 \text{ cases} \\
 &\text{Average minus } (t_e - t_w) = -0.79; 3 \text{ cases} \\
 &\text{Average } (t_e - t_w) \text{ regardless of sign} = \pm 0.92; 17 \text{ cases} \\
 &\text{Average } (t_e - t_w) \text{ regarding sign} = +0.64; 17 \text{ cases} \\
 &\text{Arc of great circle connecting } E \text{ and } W = \overset{o}{74.9} \\
 &T = \text{average time required to pass around a great} \\
 &\quad \text{circle, regardless of direction of progression} = \pm 0.92 \times \frac{360}{74.9} = \overset{m}{\pm 4.4} \\
 &T = \text{average time required for a great circle, if di-} \\
 &\quad \text{rection be considered} = + 0.64 \times \frac{360}{74.9} = +3.1
 \end{aligned}$$

22. Thus far then the general conclusion might apparently be safely drawn that there is a strong persistence in the progression of a sudden disturbance to the eastward at a speed such that a great circle of the Earth would be traversed in about 4 minutes, hence on the order of 100 miles per second. However, since the proof depends no little on Ellis's table, embracing time scalings which, as he himself states, may in individual cases be in error by as much as 5 minutes, it was thought highly desirable to undertake an entirely fresh investigation based on the best modern methods and under similar circumstances, so as to assure strict comparableness in the times for the various stations considered. I was so fortunate as to enlist Mr. Faris's interest and he has prepared the most valuable data bearing on the question at present available. *It is very much to be hoped that others will scale the times for their respective observatories for the same disturbances treated by Mr. Faris (Terr. Mag., XV, p. 101), using equal care and treating separately each element; the result, with all necessary data as to corrections applied, should be communicated to this Journal for publication. Two errors are to be noted here, viz., Storm No. 4 should read Feb. 9, 1907, instead of Feb. 7, and Nos. 13, 14, and 15 apply to 1909.*

Table V has been drawn up with the aid of Tables II, III, and IV given by Faris. The East Group comprises in general the three observatories, Cheltenham, Porto Rico, and Baldwin, and the West Group, Sitka and Honolulu. Occasionally the record from one or other of these observatories is missing; in such cases the figures are given in bold-faced type. After tabulating the times of beginning as derived separately from each element, *D*, *H* or *Z*, the means are next formed for each group, taking the three elements together, *DHZ*. Next the differences in the times for the two groups, *E-W* are formed for each element, as also for all of them together.

TABLE V.—Greenwich mean civil times of sudden beginnings of magnetic storms, 1906–09, as recorded at the magnetic observatories of the United States Coast and Geodetic Survey for each element separately.

No.	Date 1906-09	Greenwich mean civil times, sudden beginning storms.										Time between stations Diff. in time E-W				Direction	Arc of Great Circle through stations				
		Hour		East Group (E)		West Group (W)		Mean of D, H, Z		D	H	Z	Mean	D	H		Z	Mean			
				Dec'n D	Hor. Int. H	Ver. Int. Z	Dec'n D	Hor. Int. H	Ver. Int. Z										Mean of D, H, Z		
1	1906, July 29, . .	19	55.2	56.8	56.8	55.1	55.2	56.2	56.3	m	m	m	m	m	m	m	m	61	68	61	63
2	Aug. 7,	13	39.3	38.6	42.3	39.2	37.4	38.8	40.1	38.5	+0.1	+1.6	+0.6	+0.8	+1.6	+3.5	+1.6	61	68	52	60
3	Dec. 21, . . .	21	32.5	32.9	34.9	29.8	27.1	29.6	33.4	28.8	+2.7	+5.8	+5.3	+4.6	+5.8	+1.8	+2.3	68	68	68	68
4	1907, Feb. 9, . .	14	14.5	13.5	16.4	11.4	11.6	14.6	14.8	12.5	+3.1	+1.9	+1.8	+2.3	+0.1	+1.4	+1.4	68	68	68	68
5	July 10, . . .	14	24.1	23.8	25.3	22.2	21.6	25.2	24.4	23.0	+1.9	+2.2	+1.9	+2.2	+1.9	+2.2	+2.2	68	68	68	68
6	Oct. 13, . . .	7	43.2	43.4	46.1	41.0	40.8	44.2	44.2	42.0	+2.2	+2.6	+1.9	+2.2	+1.9	+2.2	+2.2	68	68	76	71
7	1908, Mar. 26, . .	17	41.6	40.5	44.6	42.4	42.3	45.9	42.2	43.5	–0.8	–1.8	–1.3	–1.3	–1.3	–1.3	–1.3	87	68	79	78
8	Aug. 19, . . .	0	13.0	14.2	16.0	14.8	14.6	17.6	14.4	15.7	–1.8	–0.4	–0.4	–0.5	–0.4	–0.5	–0.5	68	68	68	68
9	Sept. 11, . . .	7	21.0	20.8	23.3	22.2	20.8	23.7	21.7	22.2	–1.2	0.0	–0.4	–0.5	–0.4	–0.5	–0.5	68	68	68	68
10	Sept. 11, . . .	21	46.7	47.6	49.8	46.6	47.2	48.4	48.0	47.4	+0.1	+0.4	+0.9	+0.4	+0.9	+0.4	+0.4	68	68	76	71
11	Sept. 28, . . .	8	42.4	42.1	45.1	42.3	41.8	44.2	43.2	42.8	+0.1	+0.3	+0.9	+0.4	+0.9	+0.4	+0.4	79	79	79	79
12	Sept. 29, . . .	1	33.2	32.2	33.9	30.9	30.0	31.5	33.1	30.8	+2.3	+2.2	+2.2	+2.3	+2.2	+2.2	+2.2	68	68	68	68
13	1909, May 14, . .	4	57.1	56.1	59.1	56.0	53.4	58.6	57.4	56.0	+1.1	+2.7	+0.5	+1.4	+0.5	+1.4	+1.4	68	68	55	64
14	Sept. 25, . . .	8	40.2	39.1	40.4	41.5	41.1	42.2	39.9	41.6	–1.3	–2.0	–1.8	–1.7	–1.8	–1.7	–1.7	68	68	79	72
15	Sept. 25, . . .	11	40.2	41.4	42.4	44.2	42.6	49.0	41.3	45.3	–4.0	–1.2	–6.6	–4.0	–1.2	–6.6	–4.0	69	69	68	69
		Mean +										+1.37	+2.09	+1.84	+1.76	+1.76	+1.76	10 E	69	68	
		Mean –										–1.82	–1.08	–2.34	–1.08	–2.34	–1.08	5 W			
		N = Numerical Mean										±1.52	±1.75	±2.01	±1.76	±2.01	±1.76				
		A = Algebraic Mean										±0.31	±1.03	±0.45	±0.59	±0.45	±0.59				
		Time required to pass over a great circle for N										m	m	m	m	m	m				
		"										±8.0	±9.2	±10.5	±9.2	±10.5	±9.2				
		"										±1.6	±5.4	±2.4	±3.1	±2.4	±3.1				

Note the remarkable agreement in sign in the four columns (*E-W*). A plus sign means that the disturbance began later for the east group than for the west one; the letter *E* is accordingly assigned in the column of "direction" for a plus difference. Whether the elapsed time interval is obtained for the two groups from the elements by themselves or when combined, the same *E* or *W* is obtained practically for each column. *It will be seen that of the 15 disturbances considered, 10 progressed apparently to the east and but 5 to the west.*

The average time required to pass over the great circle arc, 69° , connecting the mean positions of the two groups is $+1.^m76$ for the *E* storms and the same amount $-1.^m76$ for the *W* ones; the numerical mean (not taking sign into account) is $\pm 1.^m76$, and the algebraic mean (taking sign into consideration) is $+0.^m59$. The speed for the numerical mean is such that if the storm progressed completely around a great circle, it would take $9.^m2$ or at about 45 miles per second; for the algebraic mean, the circuit would be made in $3.^m1$ or the velocity be about 165 miles per second.

23. It seems worth while, in view of the excellence of the foregoing data, to give another treatment. Table VI is based on Faris's Table I; it gives the times of beginning for each observatory separately—Honolulu, Sitka, Baldwin, Cheltenham, and Porto Rico, in the order of increasing east longitude. Now, however, only the mean time from the three elements *D*, *H*, *Z* is tabulated; for the comparatively few cases where one or two of the elements were lacking the missing time was supplied from that of one or more of the other elements with the aid of Faris's Table V; the figures so obtained are given in bold-faced type. Following the times for each observatory, the mean of all is formed, and next the deviations, $(t-t_m)$, of the mean from the individual observatory times, a minus sign meaning a less time than the mean of all the observatories.

The column marked "range" is the numerical sum of the algebraic maximum and minimum deviations; or it is the difference between the highest and the lowest of the recorded times of beginning of the disturbance considered. *It will be noticed that the range varies from $1.^m1$ to $6.^m7$; the average value is $3.^m3$ —over 3 times the possible error, according to Faris.*

Finally, in the last column is given the value of x (the time required to pass over a quadrant), as derived by treating the deviations, Δt , by the method of least squares, taking each disturbance by itself. A plus value of x means that the motion is to the east for the portion of the Earth under consideration, a minus sign meaning, of course, a westward progression of the disturbance; note again the preponderance of east motions. *The average value of x , without regard to sign is $\pm 2.^m26$ and with sign $+0.^m91$, so that were a complete circuit of a great circle made, the times would be respectively, ± 9.0 and $+3.6$ minutes.*

TABLE VI. *Mean Greenwich civil times of sudden beginnings of magnetic storms, 1906-1909, based on Table I by R. L. Farris. (Terr. Mag., Vol. XV., p. 101.)*

No.	Date	Mean Greenwich civil times of sudden beginnings derived from all elements D, H, Z						$\Delta t = t_m - t$						x	
		Hour	Min.	Secs.	Build.	Decl.	P. R.	Mean	Ion.	Stkts.	Build.	Decl.	P. R.		Range
1	1906 Aug. 29, . .	19	54.6	56.4	54.8	57.3	59.0	56.4	m	m	m	m	m	m	+3.27
2	Aug. 7, . . .	13	38.9	38.1	40.1	40.3	38.1	39.1	-1.8	0.0	-1.6	+0.9	+2.6	3.4	+0.68
3	Dec. 21, . .	21	28.9	28.8	33.7	32.8	34.3	31.7	-0.2	-1.1	+1.0	+1.2	-1.0	2.3	+6.17
4	1907 Feb. 9, . .	14	12.9	12.2	15.9	14.6	13.9	13.9	-2.8	-2.9	+2.0	+1.1	+2.6	5.5	+2.15
5	July 10, . .	14	22.8	23.1	24.0	24.4	24.9	23.8	-1.0	-1.7	+2.0	+0.7	0.0	3.7	+2.25
6	Oct. 13, . .	7	43.0	41.0	43.4	44.7	44.1	43.2	-0.7	-0.7	+0.2	+0.6	+1.1	2.1	+2.15
7	1908 Mar. 26, . .	17	43.5	43.0	43.7	42.3	41.2	42.7	-0.2	-2.2	+0.2	+1.5	+0.9	3.7	+2.49
8	Aug. 19, . .	0	16.0	15.3	14.7	15.4	13.4	15.0	+1.0	0.0	+1.0	+0.4	-1.5	2.5	+0.01
9	Sept. 11, . .	7	22.7	21.8	21.6	21.7	21.9	21.9	+0.8	+0.3	-0.3	-0.2	-1.6	2.6	-1.90
10	Sept. 11, . .	21	46.8	48.0	47.4	47.4	49.3	47.8	-0.1	-0.1	-0.3	-0.4	+1.5	2.5	-0.71
11	Sept. 28, . .	8	42.5	43.1	42.0	44.2	42.8	42.9	-1.0	+0.2	-0.4	+0.4	+1.5	2.5	+1.48
12	Sept. 29, . .	1	30.8	30.0	32.0	34.0	33.4	32.6	+0.2	0.0	-0.6	+1.4	+0.8	3.2	+0.52
13	1909 May 14, . .	4	54.5	57.5	58.4	57.6	56.4	56.9	-1.8	0.0	-0.6	+1.4	+0.8	3.2	+2.94
14	Sept. 25, . .	8	43.4	40.7	40.1	41.9	38.7	41.0	+0.6	+0.6	+1.5	+0.7	-0.5	3.9	+1.80
15	Sept. 25, . .	11	46.9	41.7	41.0	43.5	40.2	42.7	-0.3	-1.0	-0.9	+0.9	-2.5	4.7	-3.08
														6.7	-4.46
Mean of plus x,														+2.16	
Mean of negative x,														-2.54	
Mean without sign,														±2.26	
Mean with sign,														+0.91	

24. I have now given all the evidence regarding non-simultaneity and progression of disturbances which was before me when No. I of this series of papers was prepared. Since then additional information has been acquired as contained in the article by R. L. Faris (*Terr. Mag.*, XV, 1910, pp. 209-10). Table VII gives the times of beginning of possible "precursors" or preliminary disturbances preceding larger magnetic disturbances which have recently received the attention of de Moidrey and Faris.

TABLE VII. *Greenwich mean civil times of beginning of preliminary disturbances according to de Moidrey and Faris.*

No.	Date	Zi-ka-wei		Honolulu		Baldwin		Cheltenham		Mean time t	Deviations, $t - t_m = \Delta t$				x
		Time	El.	Time	El.	Time	El.	Time	El.		Zik.	Bon.	Bald.	Chelt.	
1	1907, Jan. 8	h m 1 45		h m 1 46.2	D	h m 1 50.7	D	h m none	..	h m 1 47.3	m -2.3	m -1.1	m +3.4	..	m +0.40
6	1907, Feb. 13	19 47		19 48.4	D	19 59.6	D	none	..	19 51.7	-4.7	-3.3	+7.9	..	+0.88
24	1908, Feb. 21	19 20		19 18.2	H	19 19.5	H	none	..	19 19.2	+0.8	-1.0	+0.3	..	-0.05
7	1907, Mar. 9	16 ?		13 56.1	H	13 44.0	H	13 41.4	D	13 47.2	..	+8.9	-3.2	-5.8	-1.86
13	1907, July, 10	11 00.5		none		none		10 21.1	H	10 40.8	+19.7	..	..	-19.7	?
Mean of plus x,															+0.64
Mean of minus x,															-0.96
Mean without sign,															±0.80

After each time entry there is a column, marked El, which gives the element, *D*, *H*, or *Z*, used in the scaling; this column for de Moidrey's times, in the absence of definite statements, must be left blank. The last column contains the values of x , again derived by least squares with the aid of the deviations, Δt , treating each disturbance separately. No value of x is given for No. 13, July 10, 1907, since there are only two recorded times, viz., Zi-ka-wei, 11^h 00.^m5, and Cheltenham, 10^h 21.^m1, hence $Z - C = +39.^m4$. Could we assume that, since the disturbance was not recorded at the two intermediate stations, Honolulu and Baldwin, it must have traveled eastward from Cheltenham to Zi-ka-wei, the large value of x , +14.^m1 would result; it was not deemed best, however, under the circumstances, to enter this value.

Summary of Results.

25. Table VIII contains the total evidence available to date regarding non-simultaneity and apparent motion of 38 sudden magnetic disturbances occurring between the years 1882 to 1909. The number of observatories contributing time data and the approximate portion of a complete circuit of the Earth embraced by them, will be found in the respective columns. The value of

TABLE VIII.—Summary of data respecting motion of 38 sudden magnetic disturbances, 1882-1909.

No.	Date of Disturbance	Gr. mean civil time	No. of Observatories	Approx. portions of earth	x= Time required for quadrant		Approx. Weight w	Times scaled by	
					E	W			
1	1902, May 8	h m	25	Whole	m	m	4	Dept. Terr. Mag. Kr. Birkeland	
2	1903, Jan. 26	11 59	17	"	+0.9	. . .	2		
3	1882, Apr. 16	various	8	Two-thirds	+0.7	. . .	1		
4	Apr. 20	23 35	8	"	+1.6	. . .	1	Individual observatory directors [Ellis Collection]	
5	June 15	3 35	8	"	+0.8	. . .	1		
6	Aug. 4	3 04	8	"	+1.4	. . .	1		
7	Sept. 12	15 48	8	"	+0.3	. . .	1		
8	Sept. 12	2 52	8	"	. . .	-0.9	1		
9	Oct. 2	9 40	8	"	+1.5	. . .	1		
10	Nov. 17	10 21	8	"	+2.5	. . .	1		
11	1883, Feb. 24	13 42	8	"	+0.5	. . .	1		
12	Apr. 3	9 01	8	"	+0.7	. . .	1		
13	July 29	23 47	8	"	+1.4	. . .	1		
14	Sept. 16	2 44	8	"	+0.7	. . .	1		
15	1884, July 2	19 16	8	"	+0.8	. . .	1		
16	Oct. 1	21 51	8	"	+1.5	. . .	1		
17	1885, June 24	22 31	8	"	+0.3	. . .	1		
18	1886, Mar. 30	8 22	8	"	+1.7	. . .	1		
19	1888, Oct. 30	19 45	8	"	. . .	-0.9	1		
20	1889, July 17	4 49	8	"	. . .	-1.0	1		
21	1906, July 29	19 56	5	One-fourth	+3.3	. . .	2	R. L. Faris	
22	Aug. 7	13 39	5	"	+0.7	. . .	2		
23	Dec. 21	21 32	5	"	+6.2	. . .	2		
24	1907, Feb. 9	14 14	5	"	+2.2	. . .	2		
25	July 10	14 24	5	"	+2.2	. . .	2		
26	Oct. 13	7 43	5	"	+2.5	. . .	2		
27	1908, Mar. 26	17 43	4	"	. . .	-1.8	2		
28	Aug. 19	0 15	5	"	. . .	-1.9	2		
29	Sept. 11	7 22	5	"	. . .	-0.7	2		
30	Sept. 11	21 48	5	"	+1.5	. . .	2		
31	Sept. 28	8 43	5	"	+0.5	. . .	2	de Moidrey for Zi-ka-wei and Paris for U. S. observatories.	
32	Sept. 29	1 33	4	"	+2.9	. . .	2		
33	1909, May 14	4 57	5	"	+1.8	. . .	2		
34	Sept. 25	8 41	5	"	. . .	-3.1	2		
35	Sept. 25	11 43	5	"	. . .	-4.5	2		
36	1907, Jan. 8	1 47	3	One-third	+0.4	. . .	1		
37	Feb. 13	19 52	3	"	+0.9	. . .	1		
38	Mar. 9	13 47	3	One-fourth	. . .	-1.9	1		
39	1908, Feb. 21	19 19	3	One-third	. . .	-0.1	1		
Weighted mean separately . . .					+1.65	-1.80			
Total weight . . .					42	15			
Weighted mean without sign . . .					±1.69				
Weighted mean with sign . . .					+0.74				

x , or the time required to pass over 90° or one-fourth of a great circle, is given in two columns according to whether the times progressed east, for which x is plus, or west, x then having the minus sign. The approximate weight to be attached to each result is assigned in consideration of all circumstances involved.

From this table the following results are derived:

Average time required if a sudden disturbance passed completely around a great circle of the Earth, whether to the east or to the west: $\pm 4 \times 1.69 = \pm 6.76$ minutes
 The velocity in this case would be: ± 99 kms./sec

Out of 38 cases, but 10 or only one-fourth show a general motion of the disturbance, for the portion of the Earth embraced, to the west, whereas for 28 the motion was eastward.

If the average algebraic motion be taken, i. e., taking account of the direction of progression, then the average time for a complete circuit, for the 38 cases considered, is reduced to: $+ 4 \times 0.74 = + 2.96$ minutes
 The velocity now would be: $+ 225$ kms./sec

The following conclusion is accordingly drawn:

Magnetic storms do not begin at precisely the same instant all over the Earth. The abruptly beginning ones, in which the effects are in general small, appear to progress over the Earth more often eastwardly, though also at times westwardly, at a speed of about 100 to 200 kilometers per second, so that if a complete circuit of the Earth were made it would require, on the average, between 7 and 3 minutes.

Just what the actual path followed by any disturbance may be, and its duration, depends upon a variety of conditions; it is, of course, no simple path. It remains to point out that the generally eastward progression of the sudden disturbances shown in Table VIII is in accord with the direction in which the negative electric currents would have to circulate around the Earth, in the upper regions, to produce the general type of disturbance here considered.

It is also worth while mentioning that the deflecting effect of the Earth's magnetic field on negative electric charges moving eastwardly in the upper regions would be to bring them down nearer and nearer to the surface; as I have shown in No. I, the ionic velocity decreases or the time of progression increases with decrease of height. On the other hand, negative charges moving westwardly are deflected away from the Earth by its magnetic field and the effect on magnetic needles is accordingly diminished with westward progression. In brief, the deflecting effect of the Earth's magnetic field would be favorable towards the maintenance easterly progressing magnetic disturbances and unfavorable for the westerly ones. Whether it is due to this fact that a sudden disturbance progresses more often to the east than to the west, is an interesting query. Further discussion must be postponed to the next number.