ON MINUTE, RAPID, PERIODIC CHANGES OF THE EARTH'S MAGNETISM.[1]

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In a previous communication to the Academy, a curve was exhibited which had been obtained at the Potsdam Magnetic Observatory by automatic photographic registration of the horizontal component of the earth's magnetic force. The striking feature of this curve was the fact that, in addition to the usual larger perturbations, there was a series of very small waves having nearly the same constant period, so that these waves could, in a certain way, be regarded as constituting the elementary pulsations of the earth's magnetism.

Since then it has been possible to obtain about sixty such curves. The sensitiveness of the intensity variometer was, as before, a very high one (1mm. of ordinate$=0.00004$ $cm^{-\frac{1}{2}}$ $g^{\frac{1}{2}}$ sec^{-1}), and for the time-scale a length of abscissa of 24cm. was taken to represent one hour, hence about twelve to sixteen times that of the usual registration.

All the results thus far prove that, with the means employed, it is actually possible to arrive at the smallest perturbations, or elementary waves, so that a further refinement of the instrumental means would not promise success.

In general, namely, the changes of the earth's magnetism take place gradually, so that the customary means of registration, in which a length of abscissa of 15mm. or 20mm. corresponds to one hour, suffices to reveal the phenomena, provided the curves are sufficiently clear and well-defined. But occasionally, on the average about every fifth or sixth day, the usual curves present at certain places a partially faded or hatched appearance. A closer examination shows that at these times there occur very small fluctuations of short period, which, in the Potsdam Observatory, were revealed only a few hours by the rather sensitive bifilar magnetometer, were shown much less frequently by the unifilar magnetometer, and not at all by the instrument for the vertical intensity—the Lloyd Balance. In how far this was due to lack of instrumental sensi-

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[1] Translated from the Sitzungsb. d. Preuss. Akad. d. Wiss. zu Berlin, XXXII, 678–486, 1897. The paper was read on June 24, 1897.

tiveness on the part of the unifilar and the Lloyd Balance must remain undecided until the time when we shall have succeeded in devising instruments for the registration of the declination and the vertical force as sensitive as those for the registration of horizontal force.

An examination of all the bifilar magnetograph traces obtained at Potsdam, since the beginning of 1890, shows that this phenomenon consists, as we shall describe more fully later on, of a series of more or less regular waves of small amplitude and short period, and that this phenomenon occurred much less frequently in the first years. It is not possible to say at present whether the latter fact is due to the increasing of the sensitiveness of the bifilar instrument since 1894 (1mm.=3.2γ, instead of 5γ, as before), and the employment of a much more sensitive paper, rendering it possible to obtain much better defined curves than formerly, or whether it is due to the fact that we are approaching the years of minimum sun-spots.

It is not necessary, perhaps, to state that the idea that these perturbations may be due, possibly, to the disturbing influence of electric cars, can not be entertained, for the reason that there are no electric cars in Potsdam, and that those of Berlin are doubtless far enough away—20 kilometers. Besides, such a disturbing influence would make its appearance *daily*.

Generally it was possible to obtain the perturbation of the horizontal force, alluded to above, with a second instrument, used as a control instrument, which was provided with scale and telescope, so that eye-readings could be made. The special intensity variometer, described in the previous communication, was set in operation, and it then registered the "elementary waves," whose presence, as stated, was revealed on the usual bifilar trace, by the partially faded or hatched appearance of the trace, at the time when the "elementary waves" were in progress. In this way it was possible to ascertain the time of occurrence, as well as the character of the phenomenon in question. It would appear thus far that these waves are more likely to occur during the day, and very seldom at night, whereas in the night hours take place frequently larger, even macroscopic, waves, easily recognizable on the usual traces, their vibration period being usually several minutes, the whole phenomenon lasting rarely more than one hour, generally much less. These large disturbances have received special attention at the Potsdam Observatory since 1890, as the clearer definition of the

Potsdam traces and the larger time scale employed rendered this more easily possible than at the other observatories. Since then this class of waves, or disturbances, has been subjected to a careful study by Dr. Arendt, of the Potsdam Observatory. He is inclined to deduce a relationship between them and atmospheric electric phenomena.[1]

The vibration period of the waves in question in this paper is about 30 seconds, the entire phenomenon lasting usually three to four hours, and occurring most frequently during the interval from 6 A. M. to 6 P. M., or at a time when the sun is above the horizon. A direct influence due to solar radiation has as yet not been detected, the waves appearing equally as well on cloudy days (sky uniformly overcast) as on cloudless days.

Recently, F. Kohlrausch[2] has related that he noticed, by direct eye-readings, on November 20, 1882, at Wurzburg, rapid changes of the earth's magnetism, which took place in even shorter time. His curve, drawn with the aid of the observed eye-readings, shows waves whose length, expressed in time, is on the average but 12 seconds, whereas, as will be remembered, the average length of our waves, as given in the first communication, was 30 seconds. It is not possible to say whether both kinds of waves are to be referred to the same cause, since Kohlrausch's observations were made at a time when occurred one of the largest magnetic storms recorded in recent times. From November 17th to 20th the magnetic needles at all the observatories on the globe were subjected to such violent disturbances that, in spite of the recently introduced bromide-silver paper, the trace was at times either wholly or partially obliterated. The storms of 1859–61 and 1870–71, which were possibly even more severe than the one of 1882, were doubtless registered even less completely, because of the less perfect photographic means.

The fact that disturbances so large and rapid as those of November 20, 1882, should be accompanied by minute waves is certainly highly interesting, and testifies to the importance of our problem—to resolve, by refinement of photographic registration, the earth's magnetic phenomena into its last components, or, as we may say, into its elements. Naturally, with such a sensitive

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[1] TH. ARENDT: Beziehungen der electrischen Erscheinungen unserer Atmosphäre zum Erdmagnetismus. *Das Wetter*, Heft 11 und 12, 1896.

[2] F. KOHLRAUSCH: Ueber sehr rasche Schwankungen des Erdmagnetismus. *Wied. Ann.* Bd. 60, No. 2, pp. 336–339.

intensity variometer as ours, only disturbances of moderate range could be registered, so that our results and those of Kohlrausch are not immediately comparable. It seems, in fact, that our waves are typical of magnetically calm periods. This, of course, does not exclude the possibility that the minute waves accompanying large disturbances are the same as ours, only slightly modified.

As already stated, the average length of the elementary waves was given in the first communication as 30 seconds. The many registrations obtained since slightly modify this result, and present another phase of this interesting phenomenon, the exposition of which is the chief purpose of this paper.

It might be mentioned first, that since the end of October, 1896, waves shorter than 30 seconds occurred only on two days; namely, November 7, 1896, and February 4, 1897. These series show a perfect periodicity only for short stretches, the length of the waves being about 12–15 seconds, and their range but half of that of the usual elementary wave.

Another interesting phenomenon recorded repeatedly consists of wave-groups which show an analogy to tone-beats. The best example of this kind was recorded on February 14, 1897, between 10 A. M. and 2 P. M. The page opposite (Fig. 1) gives a reproduction of this case on the original scale. It will be seen that maxima and minima are clearly discernible, and divide the curve into groups, as *aaa* and *bbb*. The latter groups, separated from each other by the vertical lines, indicate the law so distinctly that an analysis of the phenomenon should be easily possible.

We have before us, then, a phenomenon precisely similar to the one well known in acoustics; namely, the superposition of one wave system upon another, the vibration numbers of the two wave-motions differing but slightly from each other.

Letting a_1 and a_2 equal the *semi-ranges*, or *amplitudes*, of the two wave motions, T_1 and T_2 the *vibration periods*, T the period of a *tone-beat interval*, we can represent algebraically the two wave-motions by the following well-known formulæ:

$$y_1=a_1 \sin \tfrac{2\pi}{T_1} t \quad , \quad y_2=a_2 \sin \tfrac{2\pi}{T_2} (t-\tau),$$

in which τ stands for a possible phase displacement. We have, besides, $T_1=mT$, $T_2=nT$, where m and n represent the vibration numbers. The resulting wave is then:

$$y=y_1+y_2=a_1 \sin \tfrac{2\pi}{T} \cdot \tfrac{t}{m}+a_2 \sin \tfrac{2\pi}{T} \ \tfrac{t-\tau}{n}$$

Counting off the waves in Fig. 1, the value of 4:5 is obtained for the ratio $m:n$. A single tone-beat has, on the average, a length of 11.4mm., corresponding to a period of 171 seconds, and hence $T_1=43$ and $T_2=34$.

For the purpose of comparison, Fig. 2 gives a graphical representation of the two wave-systems in which exists the relation $m:n :: 4:5$. The middle curve represents the curve resulting from the superposition of one of these systems on the other. It will be readily seen that there is a remarkable similarity between this resultant curve and the one indicated by *bb* in Fig. 1. The hypothesis, then, that the phenomenon is really to be ascribed to the combination of two wave-motions of nearly equal range and slight phase difference seems justifiable.

Since the wave-groups *aa* in Fig. 1 have been registered much more frequently than the *bb* ones, it would appear that the ratio between the vibration numbers does not remain entirely constant, and that at times, also, a phase displacement takes place.

There remains to be answered one objection, which can be made with justice; namely, that instrumental causes—for example, the mechanical vibration of the needle itself—may have operated in the production of the waves under discussion.

In the first communication, attention was called to the fact that the small magnetized steel mirror of the intensity variometer is strongly damped, the damping ratio being about 4, so that, with a period of 8 seconds, *mechanical* vibrations no longer come into question. This result will be all the surer, if we obtain the same phenomenon with a second and entirely differently constructed apparatus. Reference has already been made to the fact that the waves are likewise recognizable—to be sure, not with such distinctness—with the ordinary registering instrument, and also that they can be discerned at the eye-reading instrument, our "control bifilar," which we use daily in our work for the sake of comparison, the change of scale zero being controlled by absolute observations on three days in each month. While the special-intensity variometer was being set to work, eye-readings were taken at the "control" instrument. A graphical representation suitably reduced is given in the upper curve of Fig. 4, while below we have in natural size the curve as obtained by the intensity variometer. The accord between the curves is certainly a most satisfactory one, especially when we consider that the degree of sensitiveness of the instruments differed greatly; for the "control" instrument $1\ d.=2.7\gamma$, and for the variometer 1mm. of ordinate$=0.4\gamma$. The latter instrument has a steel mirror of 20mm. diameter, placed at right angles to the magnetic meridian by imparting a proper amount of torsion to the quartz fibers supporting the magnet, whereas in the "control" instrument there is an 11 cm. long collimating magnet suspended bifilarly, and damped so that its vibration period is about 8 seconds, the damping ratio being but 2.6. The difference in the construction of the two instruments could therefore hardly be greater. The accord between the two has moreover been proven in another connection by direct observations[1] made every 5 seconds.

In order to show again that the law pervading the wave motions *bb*, in Fig. 3 is the result of *external* forces only, an endeavor was made to obtain these waves in some artificial manner.

Let us take a short magnet—for example, a piece of a magnetized knitting-needle 4 cm. long— and place it horizontally in the magnetic meridian at a distance of 1.5m. from the steel mirror placed perpendicularly to the meridian. The small steel magnet at the distance given will be deflected 3–4 minutes of arc, a quantity which represents on the curve about the same number of millimeters. If we place the small magnet vertically, and at the same height as the steel mirror, we obtain no deflection. As we turn the small magnet back, however, into its primary, horizontal position, the angular deflection will continue to increase until the maximum value given above is reached. Since the effective magnetic moment is proportional to the cosine of the inclination of the needle, or to the sine of the co-inclination, the law of increase of angular deflection would be the sine law, such as we have graphical representations of in the upper and lower curves of Fig. 2. The interaction of two such magnets, which lie either beside each other or above one another, would vary of course with their relative position, sometimes a summation of effects, at other times a counterbalancing would occur. A simple apparatus was next constructed, consisting of two drums, whose diameters were 4 and 5 cm., respectively, and the two were connected by an endless cord. To the drums were next fastened the small magnets, whose moments were about equal, for example, 16 and 18 cmgr. units, and which were 1.76 meters distant from the needle of the magnetometer. As the drums were revolved, the magnets assumed successively the positions corresponding to those of the two wave motions. With the hand, one drum

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[1] M. ESCHENHAGEN: Ueber Simultan-Beobachtungen erdmagnetischer Variationen, *Terrestrial Magnetism*, Vol. 1, p. 59, 1896.

Fig. 1.

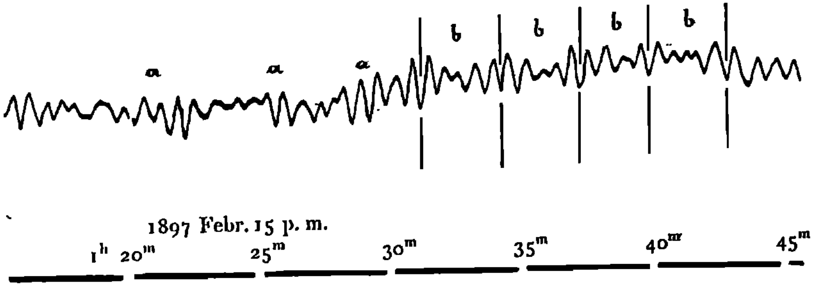


Fig. 2.

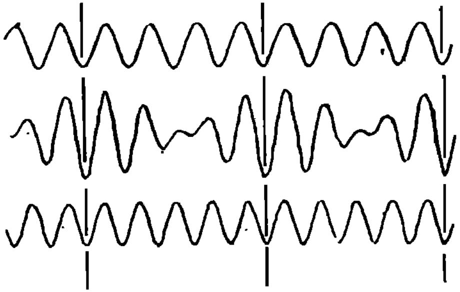


Fig. 3.

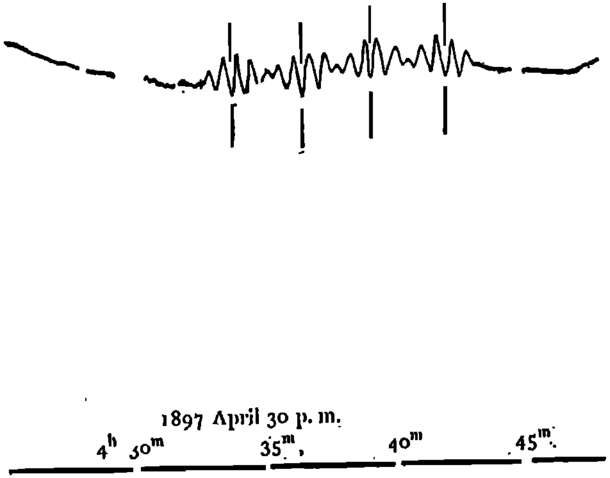
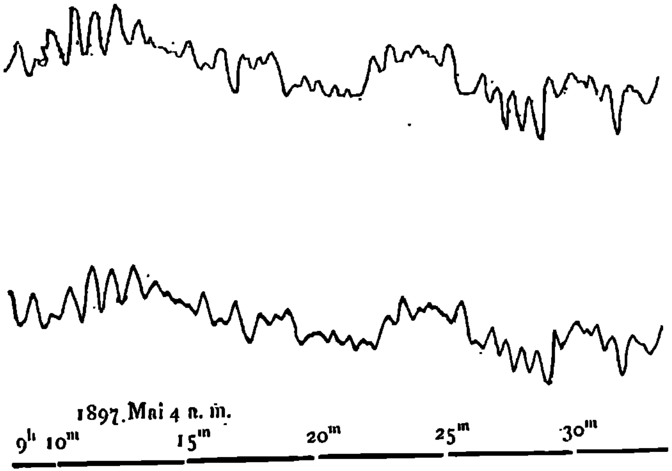


Fig. 4.



was turned out of the initial position, in which both magnets were parallel and vertical, and revolved completèly once in 40 seconds, according to the beat of a chronometer. The other drum then made the complete revolution in 32 seconds, and the registering apparatus recorded the wave groups indicated by the vertical lines in Fig. 3; whereas the earth's magnetic force proceeded gradually, as will be seen from the parts of the curve, Fig. 3, before and after the wave groups. The indisputable similarity between these waves and those of Fig. 1 proves that the needle is subjected continuously to external influences, so that we are justified in drawing the conclusion that there actually occur in nature at times similar periodically increasing and decreasing forces which affect the earth's magnetism, and which occasionally, by superposition, produce a phenomenon similar to that of tone beats. The following data will give us the magnitude of these forces. From the maximum range, 6mm., of the waves *bb*, (Fig. 1,) we find the ranges of the wave systems, taking them as equal, to be 3mm., which corresponds to a change of the horizontal component of the earth's magnetic force of $1.2\,\gamma = 0.000012$ cm.$^{-\frac{1}{2}}$ $g^{\frac{1}{2}}$ sec.$^{-1}$

Of special importance is the question as to the local distribution of these elementary waves, with regard to which, to be sure, but few investigations are at hand.

In 1895, in conformity with an agreement between Herr Stück, of the Wilhelmshaven Observatory, and myself, magnetic observations were made by us every five seconds, at precisely the same times, and at stated hours. Other observatories followed, and in 1896 fifteen observatories took part, there being four of these "term" hours. These observatories were distributed over the globe, though not uniformly. The first intention of these observations was to ascertain as accurately as possible the simultaneity in occurrence of the larger magnetic disturbances, over widely distributed areas, a fact already made very probable by the old observations of the Magnetic Association. In this way was obtained at the same time material for our present purpose.

The results obtained thus far show that large disturbances suffer from place to place not inconsiderable modifications.[1] With regard to the small waves in question here, no general result can as

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[1] A more detailed account will appear later, viz., in VEROFFENTLICHUNGEN DES K. METEOROLGISCHEN INSTITUTS: *Ergebnisse der Magnetischen Beobachtungen in Potsdam*, Anhang, 1896.

yet be deduced, as the instruments employed at the various observatories differed too greatly in the matter of sensitiveness.

From the 1895 observations, however, especially those from May 18th to June 11th, it can be seen that at Potsdam and Wilhelmshaven, there were a few series of elementary waves, which within the limit of the observing error (1–2 seconds) occurred simultaneously. In a paper written at that time,[1] it is mentioned that, in the course of an hour, about 120 turning points were observed at both places. The curves, exhibited before the meeting of the Deutsche Naturforscher at Lübeck, reveal waves of 40–50 seconds in length, which were shown up strikingly at both places. On account of the want of proper registration means at that time, it was not possible to recognize that we really had before us the smallest changes of the earth's magnetism.

From this it would appear that these elementary waves may occur simultaneously, within one second or a few seconds, over a somewhat large area; but a final conclusion will only be possible when we have before us simultaneous registrations from more places. The decision reached by the directors of meteorological institutes at their meeting in Paris, 1896, will doubtless assist in bringing about, soon, international coöperation in these investigations. When we have drawn the final conclusion, then first can we approach the question as to the origin of these waves with some degree of success. At present we can only speculate.

Recalling that, according to the investigations of Schuster[2] and von Bezold,[3] we must refer the origin of the large diurnal waves to the highest layers of the atmosphere, it may be permissible to surmise that these smallest waves likewise have their rise in this region, if special solar phenomena are not the primary cause. As these waves proceed through the air, they may be modified by the sun's rays in a manner similar to that in the case of electric discharges. Furthermore, the conductivity will be very different for those currents induced in the earth, which currents in turn again influence our needles, and in this way may it be possible to explain the change in the vibration number of the second wave system. Finally it will be of importance to investigate whether the distribution of electric waves passing into different media can cause such a slowing

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[1] *Terrestrial Magnetism*, Vol. I, pp. 55–61.

[2] *Phil. Trans. R. S.*, Vol. 180, A. pp. 467–518, 1889.

[3] Zur Theorie des Erdmagnetismus, *Sitzber. d. Pr. Akad. d. Wiss. zu Berlin*, xviii, 1897.

up of the period as is actually found. There remains the possibility of assuming that magnetic effects are produced in a manner similar to that of Röntgen's;[1] namely, by various displacements of the dielectrically polarized atmosphere with reference to the earth's surface and the highest conducting layers of the air.

As an aid in observing rapid and small changes of the earth's magnetism, the use of large wire-spools might recommend itself—a suggestion which I have already made some time since.[2] As is well known, Dr. Giese had already measured, in 1883, at the German polar station, Kingua-Fiord, the induction of the earth's magnetism in a large plane circuit, embracing about 8 square kilometers, the method used being that suggested by Werner von Siemens. He found that the currents ran parallel to the changes of the earth's magnetic vertical force, and hence were directly proportional to these changes, and inversely proportional to the corresponding time interval. This shows that the method is especially sensitive for the purpose of measuring very rapid and small changes of the earth's magnetism.

If we use, in place of the large circuit, a large wire-spool of sufficient winding area, we shall likewise obtain, with a sufficiently sensitive galvanometer, induction effects from the earth's magnetism, and have the advantage besides of being able to place such a spool in the direction of the various components, or of the total force of the earth's magnetism. The slow diurnal magnetic changes do not enter any longer into account, and the galvanometer will reveal best the most rapid changes. In this way we obtain an instrument which operates like the galvanometers which are used in the measurement of telluric currents, and which likewise respond best to the rapid changes of the earth current.

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[1] Electrodynamische Wirkung bewegter Dielectrica. *Sitzungsber. d. Pr. Akad. zu Berlin*, 1888, pp. 23-28.

[2] Internationale Polar Forschung, 1882-83. *Ergebnisse der deutschen Stationen*. Bd. I., Kingua-Fiord, pp. 597 and 598, Berlin, 1886.