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UNREASONABLE DISCRIMINATION OF BIRKELAND'S CURRENT-SYSTEM IN THE HISTORY OF MAGNETIC STORM STUDIES

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Abstract: In his pioneering study of polar magnetic storms BIRKELAND proposed in 1908 (when the existence of the ionosphere was still unknown to us) an hypothetical current-system in the earth's environmental space (which consists of an east-west horizontal electrojet above the auroral zone connected to a pair of field-aligned currents) that explains the world geomagnetic disturbance of the simplest morphological pattern called now magnetic substorm (polar elementary storm, according to BIRKELAND's original naming). In the history of magnetic storm studies, however, BIRKELAND's idea was discarded in 1938 but revived in 1950's. This historical fact seems to have resulted from an unreasonable discrimination against his current-system in a comparison with that of CHAPMAN, wherein the proposed BIRKELAND current-system was unfortunately misrepresented. This unintentional mistake has remained unnoticed over half a century.

1. Introduction—Two Great Contributors to the Study of Magnetic Storms

In the history of magnetic storm studies Kristian BIRKELAND [1867–1917] and Sydney CHAPMAN [1888–1970] made great contributions to the analysis of magnetic field disturbances over the world through presenting their own hypothetical electric current-systems in the earth's space environment, which give the same magnetic field as that observed actually on the ground. Both BIRKELAND and CHAPMAN were fully aware that it was absolutely impossible to obtain any current-system uniquely from observations on the ground alone.

From the 1940's to 1960's there was a serious debate between CHAPMAN and ALFVÉN on their preference of space current-systems for magnetic storms; ALFVÉN advocated the importance of field-aligned currents, whereas CHAPMAN wished to attribute the ground magnetic effect wholly to horizontal currents flowing entirely in the ionosphere. A simple intuitive proof has been given (FUKUSHIMA, 1969, 1976) for the equivalence in ground magnetic field produced by substorm current-systems proposed by BIRKELAND and CHAPMAN, but it still remained as a mistery why BIRKELAND's current-system had to be discriminated in the late 1930's. This paper gives an answer to this question, which was obtained through checking the old literature concerned.

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2. BIRKELAND's and CHAPMAN's Current-Systems for Magnetic Substorms

BIRKELAND was the first scientist to study geomagnetic disturbances by utilizing magnetogrammes at various stations over the world, especially those obtained during the First International Polar Year of 1882–83 and his Norwegian Aurora Polaris Expedition 1902–03 (BIRKELAND, 1908, 1913). After studying a number of individual magnetic disturbances, he classified them into the following five categories: positive and negative polar elementary storms (substorms, according to modern terminology), positive and negative equatorial storms (initial and main phases of magnetic storms), and cyclomedian storms (now called s.f.e.'s). He attributed a typical negative polar elementary storm to such a simple electric current-system in the earth's environmental space as that shown schematically by (A) of Fig. 1, which consists of a pair of field-aligned currents connected to a westward horizontal current flowing at a height of a few hundred km above the ground.

On the other hand, CHAPMAN's investigation of magnetic storms was after BIRKELAND's time, and he published a number of influential papers with his models of the ionospheric current-systems (CHAPMAN, 1919, 1927, 1935). In contrast to BIRKELAND, CHAPMAN emphasized the importance of studying an average morphology of magnetic storms, and he expected that individual storms would not deviate so significantly from the average magnetic storm (according to SUGIURA, 1984). However, in his later papers (*e.g.*, AKASOFU and CHAPMAN, 1961), he recognized the concept of *substorms* that are exactly the same as BIRKELAND's *polar elementary storms*. CHAPMAN attributed a negative polar substorm to such an electric current-system as (C) of Fig. 1 situated in the lower ionosphere (*E*-region, so-called the dynamo region).

Figure 2 shows an intuitive explanation (FUKUSHIMA, 1969) for the equivalence in the ground magnetic effect of (A) and (C) current-systems, because current-system (A) of Fig. 1 can be reasonably approximated by (A) of Fig. 2 insofar as the ground magnetic effect is concerned, and the current-system of (B)=(A)−(C) produces a magnetic field only above the ionosphere. A vertical current into (out of) the iono-

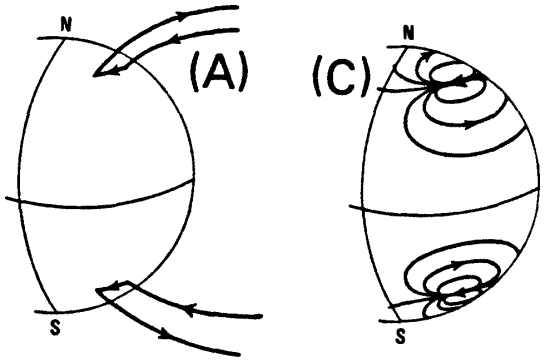

Fig. 1. Electric current-systems over the earth for typical magnetic substorms, viewed from the evening side; (A) proposed first by BIRKELAND and advocated later by ALFVÉN and (C) by CHAPMAN.

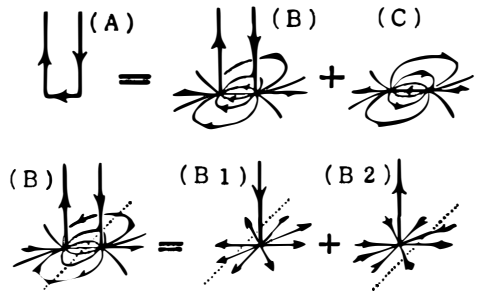

Fig. 2. Diagrams showing the equivalence in ground magnetic effect of current-systems (A) and (C), because no magnetic field is produced below the ionosphere by current-system (B)=(B1)+(B2).

sphere does not produce any magnetic field below the ionosphere if it is combined with the ionospheric current of uniform divergence from (convergence to) the foot of the vertical current.

3. Unreasonable Comparison of BIRKELAND's and CHAPMAN's Current-Systems

The most influential paper contributed to the neglect of BIRKELAND's current-system seems to be a paper by VESTINE and CHAPMAN (1938), which compared CHAPMAN's S_D current-system (Fig. 3A) with that of BIRKELAND (not his own but by the authors, shown herewith in Fig. 3B). They stated as follows referring to their diagram (Fig. 18 of their 1938 paper; reproduced here in Fig. 4): "In the case of BIRKELAND's model a good fit with observation near the auroral zone implies a poor

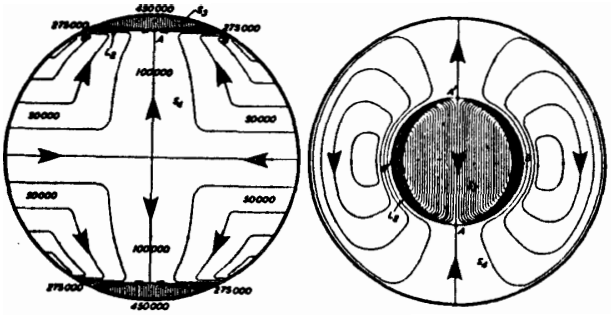

Fig. 3A. Current-system for geomagnetic S_D-field (diurnally varying part of ground magnetic field observed on disturbed days) proposed by CHAPMAN, viewed from the sun (left) and from above the north pole of the earth (right) (taken from Fig. 1 of VESTINE and CHAPMAN, 1938).

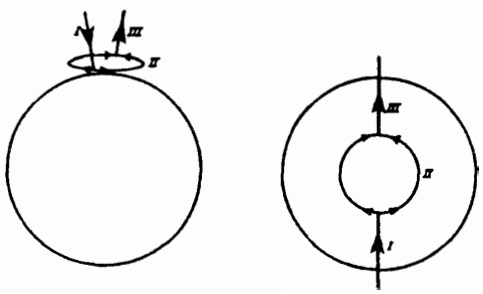

Fig. 3B. BIRKELAND's current-system for S_D-field (not his own, but presented by VESTINE and CHAPMAN as Fig. 17 in their 1938 paper to compare its ground magnetic effect with that of Fig. 3A current-system), viewed from the early afternoon side (left) and above the earth's north pole (right).

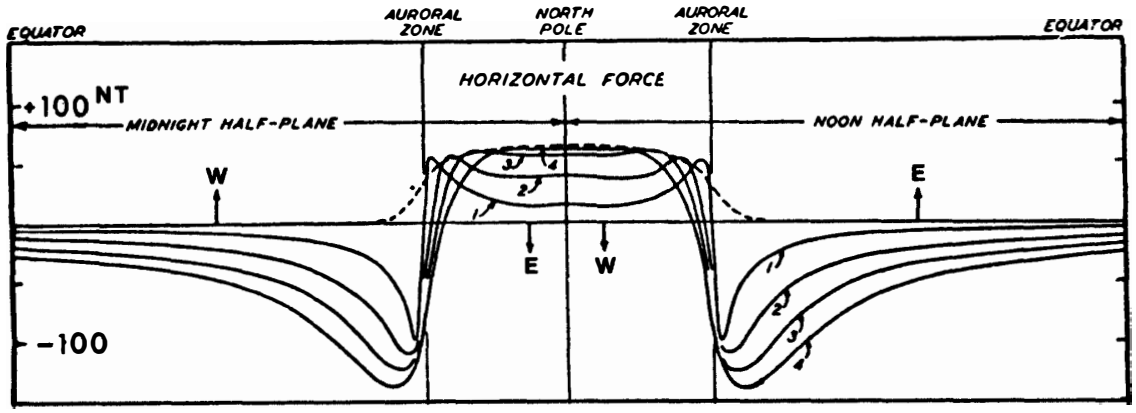

Fig. 4. East-west magnetic field on the ground produced by the current-system of CHAPMAN (with dotted lines) and of BIRKELAND (full lines; 1, 2, 3, and 4 refer respectively to assumed heights of the auroral zone current, 100, 300, 500 and 700 km above the earth). This diagram is taken from Fig. 18 of VESTINE and CHAPMAN (1938) paper.

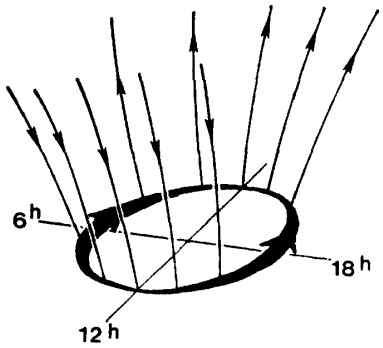

Fig. 5. BIRKELAND's S_D current-system that should have been compared with CHAPMAN's Fig. 3A current-system. Field-aligned currents flow in all longitudes, downward on the dayside and upward on the nightside.

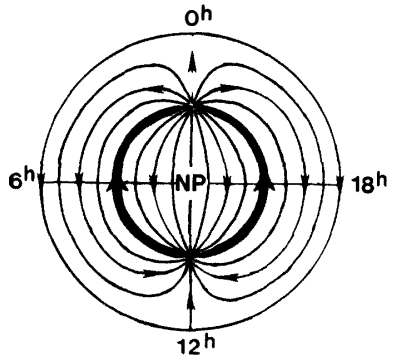

Fig. 6. Equivalent overhead current-system of Fig. 3B current-system, which produces an intense E-W magnetic field on the ground near the noon-midnight meridian, especially in the region immediately outside the auroral zone.

fit with observation near the center of the auroral zone, and vice versa, and this fact, together with other objections which might be raised (CHAPMAN, 1935) suggests that *BIRKELAND's current-system be discarded as unsatisfactory in its agreement with observation.* It does not appear possible that a drastic modification of the model will result in a great improvement with the general fit obtained with the observed data as given here".

The above conclusion by VESTINE and CHAPMAN must have originated from an incorrect modification of BIRKELAND's idea, *i.e.*, they should have represented as BIRKELAND's S_D current-system (even though he never showed such a statistical one), a current-system shown in Fig. 5, because it is desirable to compare two current-systems with the same electrojet configuration along the auroral zone. Figures 3A and 5 (both with the same longitude-dependence in their electrojet intensity) give the same magnetic effect on the ground, and this can be simply understood with the aid of the theorem demonstrated by Fig. 2. It is also worth mentioning that ALFVÉN's experiment succeeded in explaining the observed morphology of the ground magnetic field by the magnetic effect from wire currents (like Fig. 5) above the model earth; this esperiment was carried out as a support to his new theory of magnetic storm (ALFVÉN, 1939, 1940).

The equivalent overhead current for Fig. 3B current-system is the one shown in Fig. 6, because the two vertical line-currents in Fig. 3B can be replaced by horizontal currents diverging and converging uniformly in the ionosphere from and to the points of vertical current inflow and outflow. It is clear in Fig. 6 that the equivalent overhead current is considerably strong at high and middle latitudes near the noon and midnight meridians in comparison with other local time meridians, and this is revealed in Fig. 4 in the eastward magnetic field in the midnight meridian and the westward magnetic force in the noon meridian on the ground outside the auroral zone. VESTINE and CHAPMAN used Fig. 4 (which is the bottom diagram of Fig. 18 in their 1938 paper) to reject BIRKELAND's current-system in interpreting the geomagnetic

field disturbance during magnetic storms.

It is highly possible that CHAPMAN was not at all aware of this mistake until he passed away in 1970, because we find the following statement in his opening speech of the BIRKELAND Symposium on Aurora and Magnetic Storms held in Sandefjord, Norway, 18–23 September 1967 for his 100th anniversary (CHAPMAN, 1968). "The Second International Polar Year, 1932/3, provided material for new advances in our knowledge of magnetic storms, when the records were discussed, especially by VESTINE (1940). He and I (1938) also compared the records with the polar electric current-systems proposed respectively by BIRKELAND (1908) and myself (1935). Mine were located entirely in the ionosphere, whereas BIRKELAND postulated currents carried by electron streams from the sun, entering the atmosphere nearly vertically, and after flowing along the auroral zone for some distance, departing upwards into the space beyond. Our results favored my system rather than BIRKELAND's, and KIRKPATRICK (1952) reached the same conclusion from an independent study some years later, which dealt also with a model given by ALFVÉN (1940)".

4. KIRKPATRICK's Calculation of the Magnetic Effect from Model Currents

KIRKPATRICK (1952) rejected BIRKELAND's, ALFVÉN's and his own current-systems (all with auroral electrojets connected to field-aligned currents) as possible sources of the diurnal variation (S_D) of magnetic disturbance, after calculating the ground magnetic effect from all these model current-systems. Figure 7 compares his calculated values for the east-west magnetic field with smoothed observed values (this diagram is Fig. 6 of his 1952 paper), similarly to Fig. 4 in this paper. The curves shown in Fig. 7 are:

Birkeland 300 km ..... BIRKELAND's current-system (misrepresented in the VESTINE-CHAPMAN 1938 paper) with its auroral-zone current at a height of 300 km at colatitude 23°.

Alfvén 300 km ..... ALFVÉN's current-system with its auroral-zone current at a height of 300 km, at colatitude 23°.

Kirkpatrick 400 km .... KIRKPATRICK's current-system (Fig. 1 of his 1952 paper; similar to ALFVÉN's one, but with a sunward current on the equatorial plane at 6.9 earth radii to keep the current divergence-free); its auroral-zone current at colatitude 23°, height 400 km.

Smoothed observed values with the scale on the right side (the scale for the above three calculated values is on the left side) of Fig. 7. The observed values show a noticeable asymmetry in the noon-midnight meridian plane, because of an actual day-night latitude difference of the auroral-zone position. On the other hand, all the calculated curves are symmetric with respect to the pole because of a simple assumption of a fixed colatitude for the auroral zone. Notwithstanding this idealization for the calculated curves, it is worth noting in Fig. 7 that the "Alfvén 300 km" and "Kirkpatrick 400 km" curves show a latitude-dependence of the calculated disturbance field similar to that of the "smoothed observed values". Note here also that the intensities of all

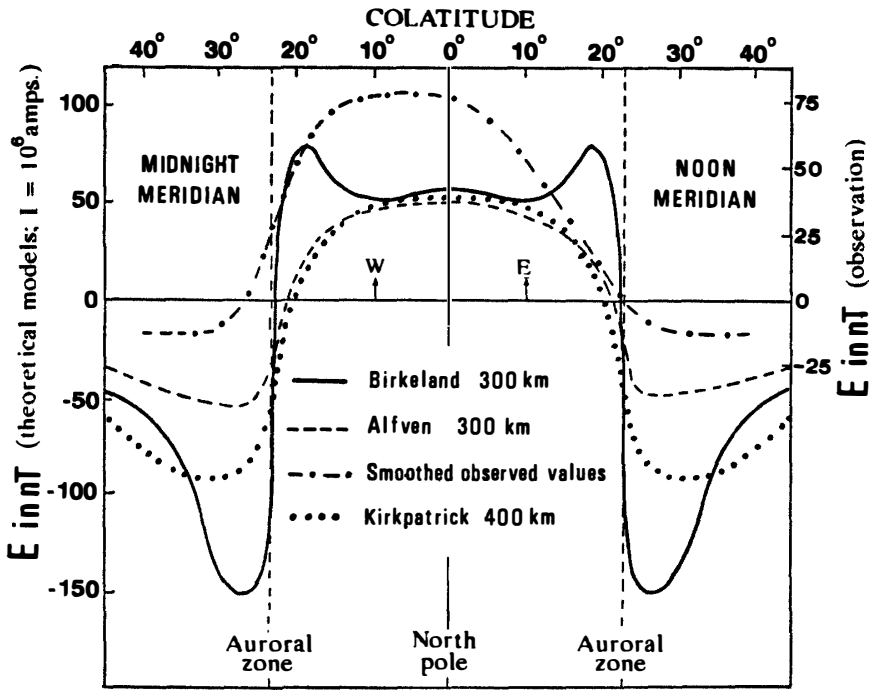

Fig. 7. East-west magnetic field on the ground produced by BIRKELAND's ALFVÉN's *and* KIRKPATRICK's *current-systems over the earth (the heights of horizontal currents in their models are indicated in this diagram) and smoothed observed values, reproduced from Fig. 6 of* KIRKPATRICK's *(1952) paper. For the calculated curves the current intensity is given so as to produce the ground magnetic field of 50 nT at the north pole of the earth, and the auroral zone is assumed to be fixed at 23° colatitude circle. The noteworthy deviation of the "Birkeland 300 km" curve from the other two calculated curves must have originated from the misrepresentation of* BIRKELAND's *current-system by* VESTINE *and* CHAPMAN *pointed out in Section 3.*

the model currents are chosen so as to produce the same value of 50 nT at the pole of the earth's surface. If the model current intensities in KIRKPATRICK's calculation were taken 1.5 times stronger (witch is not at all unreasonable), the calculated and observed E-values inside the auroral zone (colatitude$\leqq$23°) will show an excellent agreement one another, if the auroral-zone shift towards low latitude in the midnight meridian is also taken into account.

Outside the auroral zone, large negative calculated E-values seem to be resulted from various reasons, such as the fixing of the auroral zone at 23° in colatitude, a simple line-current assumption for the auroral electrojet, and so forth. It must also be remarked that the smoothed observed values are obtained after averaging a great number of magnetic disturbances with different grades of activity (*i.e.*, different latitudes of the auroral electrojet), and this will probably cause a reduction of statistical E-value observed outside the auroral zone. Hence, we do not need now to pay too much attention to the apparent discrepancy between the calculated and observed E-values outside the auroral zone until the calculation is improved with a more realistic model for the auroral electrojet.

It is also worth noting in Fig. 7 that the "Alfvén 300 km" curve shows much smaller E-values immediately outside the auroral zone than the "Kirkpatrick 400 km"

curve. KIRKPATRICK did not show in his paper the dependence of the calculated ground magnetic effect on the assumed height of the auroral-zone current. It will be interesting to check it, because the assumed height of the auroral-zone current in his paper is a little too high. It is also a mistery for the present author why David F. MARTYN (a respected specialist in ionospheric physics at that time) instructed KIRKPATRICK to assume 300–400 km as the height of the auroral-zone current, although the height was already known even at that time to be about 100 km. Considering these circumstances in mind, we will be allowed to say from Fig. 7 that the "Alfvén and Kirkpatrick curves" agree reasonably well with the smoothed observed values. The discrepancy between their curves and the observed values (resulted partly from some idealized assumptions for the theoretical current models) will not at all be a sufficient reason to reject ALFVÉN's and KIRKPATRICK's current-systems as a possible source for the geomagnetic S_D field. On the other hand, a remarkable strange deviation of the "Birkeland 300 km" curve from all other calculated and observed curves is originated from its misrepresentation by VESTINE and CHAPMAN (1938) explained is Section 3.

5. Concluding Remarks

This paper points out that the neglect of BIRKELAND's important work in the discussion of magnetic storms in the 1940's originated in an unfortunate misrepresentation of BIRKELAND's current-system in a paper by VESTINE and CHAPMAN (1938); this mistake has remained unnoticed over half a century. We should not blame them for their unintentional mistake; they must be highly appreciated for their great contributions to modern geomagnetism. At the same time, the author is glad to know that the unfortunate event for BIRKELAND was not at all based on his own scientific fault.

Despite the unfortunate neglect of BIRKELAND's current-system for polar elementary storms since 1938, his excellent work was reasonably summarized in the monumental textbook "Geomagnetism" (CHAPMAN and BARTELS, 1940), without mentioning the rejection of his current-system discussed by VESTINE and CHAPMAN (1938), although this paper is referred to in this book to show the latest progress in the study of magnetic storm phenomena. BARTELS must have proposed the best way to deal with BIRKELAND's current-system in the textbook that played later an important role in the revival of BIRKELAND's pioneering work. Nearly half a century after his death the first experimental detection was carried out by ZMUDA *et al.* (1966) for field-aligned currents in the earth's space environment.

The author noticed in January 1989 the point described in Section 3 of this paper, while he was preparing his note for "BIRKELAND Lecture" to be held in Oslo on 24 October 1989. The note of his talk (FUKUSHIMA, 1990) was published from the Norwegian Academy of Science and Letters. The author is very grateful to the organizers of the 1989 BIRKELAND Lecture, especially to Prof. Alv EGELAND (Department of Physics, University of Oslo) for giving me an honour of being one of the 1989 BIRKELAND lecturers.

This paper contains also the author's re-examination of KIRKPATRICK's paper carried out shortly after the 1990 NIPR Symposium on Upper Atmosphere Physics held 23–24 January 1990. The author has now an impression that a goodwill of

CHAPMAN's students or co-workers to support his idea brought about an unreasonable discrimination of BIRKELAND's idea in the history of magnetic storm studies.

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