A Study of Auroral & Polar Magnetic Substorms

A Report

by

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Abstract

This study was an attempt to reproduce the field variations observed during a particular polar magnetic substorm by a simple model current system. A line current model consisting of flow down field lines, along auroral arcs and back out along field lines was used. A computer program utilizing a matrix form of the Biot-Savart law was written to calculate the effect of the model current system. Parameters of the system were adjusted to give a best fit. The westward electrojet was found to flow along or slightly poleward of the auroral forms. The eastward electrojet was found to flow slightly equatorward of the discrete aurora. Agreement of calculated and observed field variations was generally good.

A Study of Auroral and Polar Magnetic Substorms

I. Introduction

The auroral and polar magnetic substorms are two different aspects of the magnetospheric substorm. Energy from the solar wind is stored in the earth's magnetosphere and released from time to time, generating many diverse electromagnetic phenomena. These phenomena are collectively called the magnetospheric substorm. During a substorm, the aurora intensify, expand, and move towards the pole, then become less intense and recover their old form, drifting equatorward (the auroral substorm). At the same time, rapid changes in the earth's magnetic field, particularly at higher latitudes, are observed (the polar magnetic substorm).

The study of magnetospheric substorms is perhaps the most active field in near-earth space science today. During the last decade, the study of the temporal and spatial variations of the earth's magnetic field observed during polar magnetic substorms has rapidly expanded. At the same time, the current systems proposed to explain substorm field variations have evolved into complex three-dimensional systems with field-aligned and magnetospheric currents coupled to the eastward and westward ionospheric electrojets. This study presents evidence, in the form of computer-generated models, in support of a relation between the position of the current systems of the polar magnetic substorm and the position of the visible aurora of the simultaneous auroral substorm.

II. Current Systems

The idea that the magnetic variations of the polar magnetic substorm are caused by three-dimensional current systems in the earth's upper atmosphere is not new. Birkeland (1908, 1913) proposed such a current system to explain the field variations, with current flowing down along magnetic field lines to the ionosphere, westward through the ionosphere, and back up the field lines into space. Birkeland's model was ignored for almost fifty years, because, until quite recently, there was no experimental evidence of field-aligned currents. Until the late 1960's, most models consisted of current flow along the electrojets, but with return currents in the ionosphere, rather than out along field lines. During the last ten years, satellite and rocket observations have confirmed the existence of field-aligned currents, and Birkeland's model has again become popular. It is now an important part of most recent models of substorm current systems.

Two current systems which have been proposed to account for substorm field variations are shown in Fig. 1. The current system in Fig. 1a (Sugiura and Heppner, 1965) is of the type generally accepted until the late 1960's. It consists of a westward ionospheric electrojet in the midnight and morning sectors, an eastward electrojet, at slightly lower latitude, in the evening sector, and ionospheric return currents for both electrojets. The return currents form loops, both across the polar caps and down into lower latitudes.

The current system in Fig. 1b (Kamide and Fukushima, 1972) is based on Birkeland's model. It consists of westward and eastward electrojets in the same position as the model of Fig. 1a, but with return currents primarily flowing out along field lines, rather than in ionospheric loops. Much weaker ionospheric loops are included, in order to suggest that both types may be operative.

It should be noted that either of the two current systems in Fig. 1 can be modified to explain the field variations observed at the earth's surface. However, recent rocket observations provide indirect support of the second model. Sheet currents of large E-W extent have been observed flowing in along field lines, through the earth's ionosphere in a N-S direction, and out along field lines again. These sheet currents give rise to large toroidal magnetic fields in and above the ionosphere, but are believed to produce only small effects at the earth's surface. Although coupling with the electrojets has not yet been observed, the proven existence of field-aligned currents does lend support to a model of field-aligned currents coupled to eastward and westward electrojets, as illustrated in Fig. 1b.

III. Substorm Field Modelling

The model used in this study is a simplified version of the one in Fig. 1b, consisting of eastward and westward electrojets coupled to return currents along field lines. To simplify the mathematics required in the computation of the model's effects, the electrojets were restricted to lines of geomagnetic latitude (a surprisingly good approximation), line currents were used rather than sheet currents, and the weak ionospheric return current loops were not included. The resulting current model is illustrated in Fig. 2.

Early modelling attempts included a closure of the field line-electrojet-field line current loop by a current in the magnetotail. However, it was found that due to the large distance of this current from the earth's surface (approximately fifty earth radii), its effect was very small compared to the other components of the current system. As its inclusion increased the use of computer time considerably, it was omitted from later modelling attempts.

A computer program was created to calculate the effects of the model current system for any observation point on the earth's surface. Writing, correcting, and modifying it constituted a major portion of this study. The essential element of the program is a matrix form of the Biot-Savart law in spherical coordinates (Kisabeth and Rostoker, 1976).

Fig. 3a and Fig. 3b are line drawings made from computer plots of the H, D, and Z components of the magnetic field that would be observed at stations along a meridian of geomagnetic longitude passing underneath a westward electrojet. The electrojet is 20° (almost 1000 km) long, located at a height of 115 km. above the earth's surface, and carries a current of 800,000 amps. The H, D, and Z components contain contributions from the field line currents associated with the electrojet, as well as from the electrojet itself.

Fig. 3a shows the components observed along a meridian 5° east of the center of the electrojet. Fig. 3b shows those observed along a meridian 15° west of the center, that is, 5° west of the western end of the electrojet. The sign of the D component changes from the east side to the west. If observed along the central meridian of the electrojet, it would be zero at all points. It can also be seen that the H and Z components have smaller maximum values and less steep curves farther away from the center of the electrojet.

The purpose of this study was to attempt to reproduce the field variations of a particular substorm by electrojets (with associated field line currents) at or near the position of the simultaneous visible aurora. Data for the field variations and auroral positions came from a paper by Kamide and Akasofu (1975). Data used consisted of (1) DMSP satellite auroral photograph (with an accompanying sketch) taken at 2151 UT, 10 January, 1973, just after the onset of a medium-sized substorm, (2) equivalent overhead current vectors for the nine magnetic observatories listed in Table 1. Equivalent overhead current vectors are just horizontal magnetic disturbance vectors, rotated clockwise by 90^{o}. The photograph and the sketch of auroral forms on an invariant geomagnetic coordinate system were used to determine the position of the aurora in the geomagnetic coordinate system used in this study. The equivalent current vectors were rotated counterclockwise by 90^{o} to give magnetic disturbance vectors in the horizontal plane.

Next, electrojets were positioned along the auroral forms, and their parameters were adjusted in an attempt to reproduce the observed magnetic variations. As the configuration of the field-line portion of a three-dimensional current system is dictated by the earth's dipole field and the position of the auroral electrojet, the parameters of the electrojet control the entire system. Since the electrojet was confined to flow along lines of geomagnetic latitude by the modelling program, those parameters include only length of the electrojet, longitudinal and latitudinal location of its center, height above the earth's surface, and magnitude of current flow. After several attempts, the electrojets (and associated field line currents) of table 2 were selected as a final model. The westward electrojet was found to flow along or slightly poleward of the auroral forms. The eastward electrojet was found to flow slightly equatorward of the discrete aurora.

The magnetic field variations generated by this current system model are shown, along with the observed field variations and the superimposed position of the auroral forms, in Fig. 4. For the majority of the stations, agreement of observed and calculated field variations was quite good. Exceptions were the stations at Alert and Leirvogur. These are probably due to local phenomena not included in the large-scale modelling of this study. Past studies have shown the local field at Alert to be greatly affected by induction currents within the earth. Alert may also be affected more by current flow associated with polar cap aurora than by the flow along the auroral oval used in this model. As indicated by the photograph, Leirvogur is located directly underneath a westward-traveling surge. Large distortions in the local field have been reported near such surges (Kisabeth and Rostoker, 1973). In general, however, the agreement of the observed field variations with calculated effects of the model current system is good, implying that the present use of models like the one in this study to explain substorm field variations is valid.

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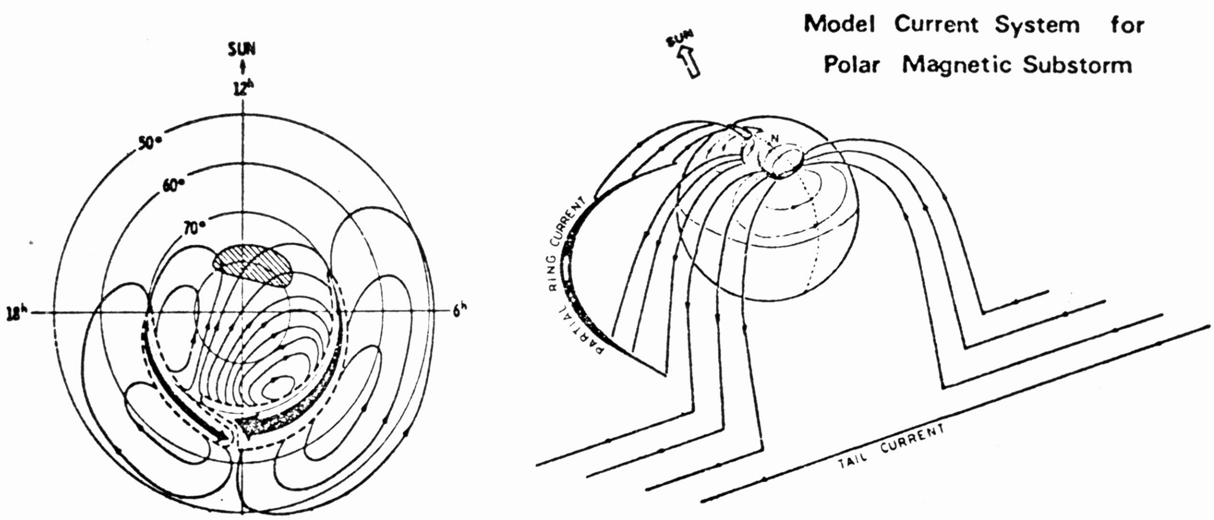

a b

Fig. 1.a. Equivalent ionospheric current system involving a strong eastward electrojet in the evening sector along with a westward electrojet in the midnight and morning sectors (after Sugiura and Heppner, 1965).
b. Equivalent three-dimensional model for the eastward and westward electrojets. From ground observations, this current system may look the same as the equivalent ionospheric current system (after Kamide and Fukushima, 1972).

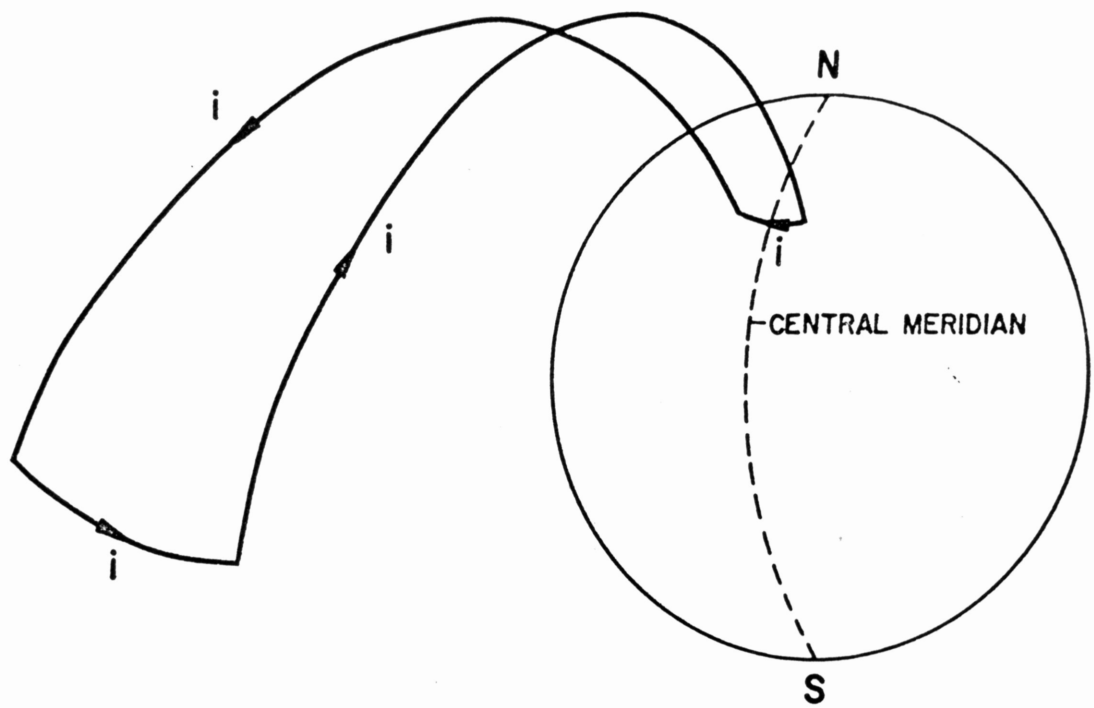

Fig. 2. Simplified model current system used in this study. A symmetrical system exists in the southern hemisphere, but has little effect on high-latitude northern hemisphere observatories.

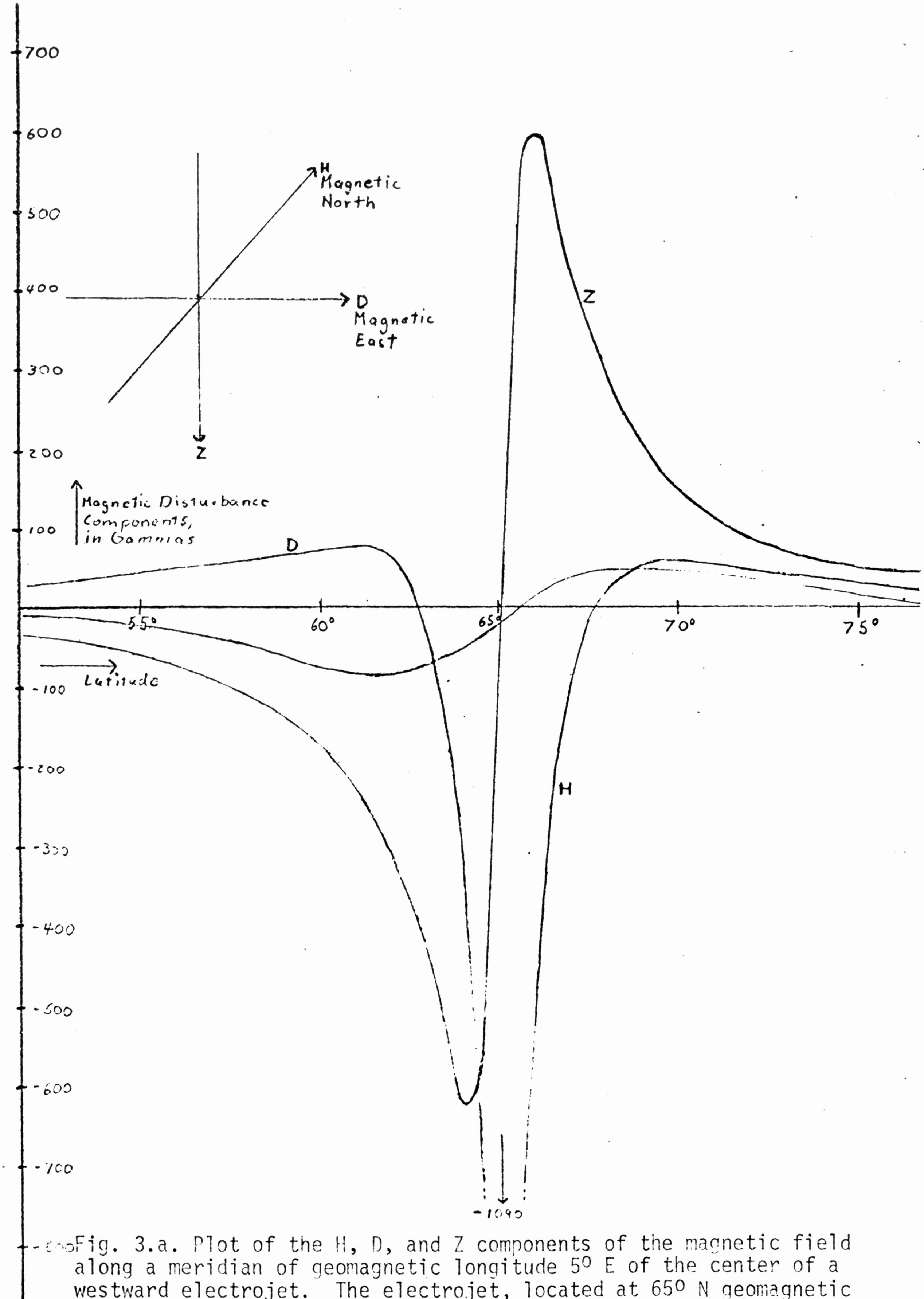

Fig. 3.a. Plot of the H, D, and Z components of the magnetic field along a meridian of geomagnetic longitude 5° E of the center of a westward electrojet. The electrojet, located at 65° N geomagnetic latitude, has a longitudinal extent of 20° and carries a current of 800,000 amps.

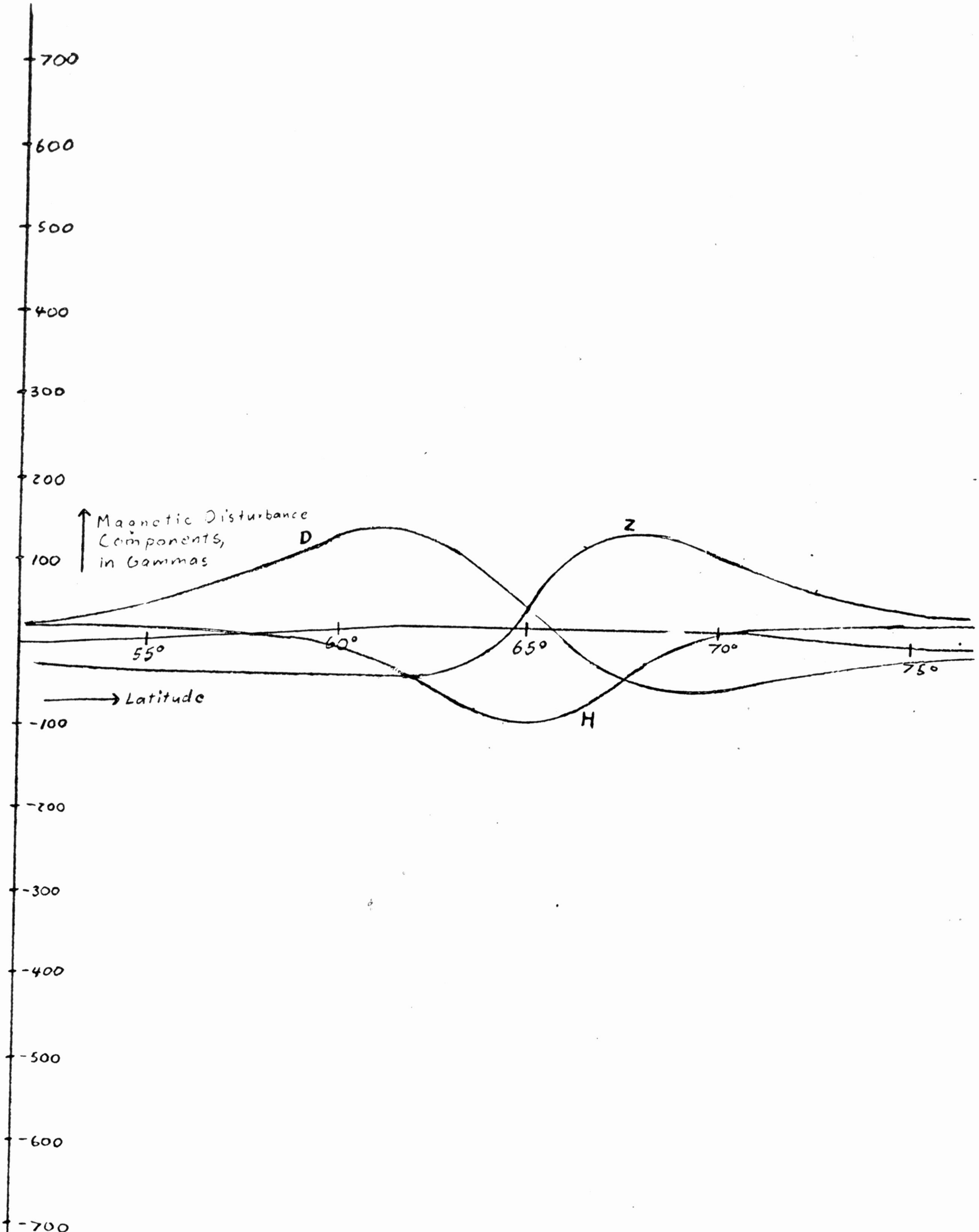

Fig. 3.b. Plot of the H,D, and Z components of the magnetic field along a meridian of geomagnetic longitude 15° W of the center of a westward electrojet. The electrojet, located at 65° N geomagnetic latitude, has a longitudinal extent of 20° and carries a current of 800,000 amps.

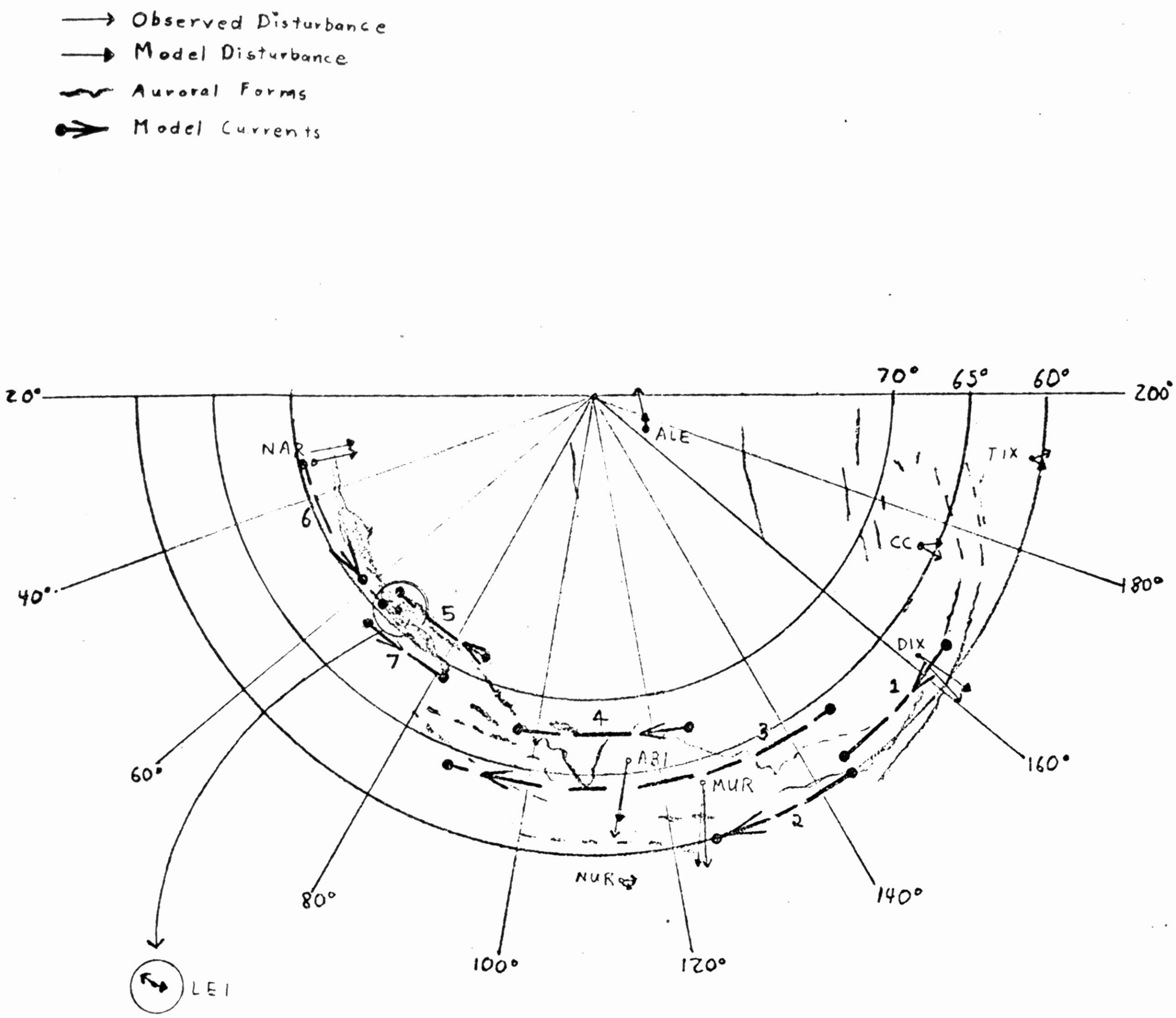

Fig. 4. Modelling results.

Table 1

Station	Abbreviation	Geomagnetic Latitude	Geomagnetic Longitude	Geographic Latitude	Geographic Longitude
Alert	ALE	85.9	168.2 E	82°30'	62°30' W
Tixie Bay	TIX	60.4	191.4 E	71°35'	129°00' E
Cape Chelyuskin	CC	66.3	176.5 E	77°43'	104°17' E
Dixon Island	DIX	63.0	161.6 E	73°33'	80°34' E
Murmansk	MUR	63.5	125.8 E	68°15'	33°05' E
Abisko	ABI	65.94	115.28E	68°36'	18°49' E
Nurmijarvi	NUR	57.9	112.6 E	60°31'	24°39' E
Leirvogur	LEI	70.2	71.0 E	64°11'	21°42' W
Narssarssuaq	NAR	71.14	37.42E	61° 2'	45°24' W

Table 2

Parameters of Model Current System

Current Number	Geomagnetic Latitude	Geomagnetic Longitude Eastern Limit	Geomagnetic Longitude Western Limit	Magnitude (Amps)
1	61.2	168	145	500,000
2	60.0	145	125	150,000
3	64.1	148	88	130,000
4	67.5	126	97	240,000
5	71.6	88	65	260,000
6	70.4	65	37	-200,000*
7	69.0	81	65	-200,000*

*A negative current indicates an eastern electrojet.