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SUBSTORM FIELDS IN AND NEAR THE AURORAL ZONE*

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During the last few years, the study of both temporal and spatial variations of substorm fields has rapidly expanded, mainly because of the relationships which exist between polar magnetic substorms and magnetospheric phenomena. Also during these years, proposed current systems believed to be responsible for substorm variations have evolved into complex three-dimensional systems with field-aligned and magnetospheric currents coupled to the eastward and westward electrojets. Recent model studies show that substorm variations in and near the auroral zone can easily be modelled using both two and three-dimensional current systems. In these studies, induction effects were simulated by assuming the Earth to be infinitely conducting at some depth below the surface.

The use of magnetometers distributed along magnetic meridians has resulted in a better understanding of the complex current patterns making up the electrojets. For example, during the expansive phase of substorms, the westward and poleward progression of the overall westward electrojet was discovered to take place through the sequential development of a series of westward electrojets.

1. Introduction

During the past decade, polar magnetic substorms have been subjected to numerous intense investigations, which has been primarily due to the realization that the "polar magnetic substorm" is an integral part of what has become known as the "magnetospheric substorm". Because of this relationship, the study of both spatial and temporal variations of substorm fields has proven to be an invaluable tool in furthering our understanding of the magnetosphere and solar–terrestrial relationships as a whole.

As a result of this growing interest in polar magnetic substorms, numerous reviews concerning substorm fields and their relationships with other geophysical phenomena have been published recently (e.g., see Akasofu, 1968; Boström, 1968; Feldstein, 1969; Hultquist, 1969; Fukushima, 1972; Rostoker, 1972a,b; Fukushima and Kamide, 1973; Rostoker, 1974a; Gough, 1974). Rather than duplicating what already exists in these recent reviews, the emphasis here will be placed primarily on temporal and spatial variations of substorm fields in and near the auroral zone, along with modelling of current systems which may possibly be responsible for these variations. Such a review should be of particular interest to scientists studying electromagnetic induction in the Earth by non-uniform sources such as the auroral electrojets (i.e., Hermance and Peltier, 1970; Hibbs and Jones, 1973; Nopper and Hermance, 1974).

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2. Substorm current systems

For some time it has been known that current systems in the Earth's upper atmosphere are responsible for large magnetic variations observed during auroral displays in the polar regions. The first definitive study of such current systems was done by Birkeland (1908, 1913; see Boström (1968) for these references), who concluded that the current system associated with, what he termed "polar elementary storm", was three-dimensional in nature 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 polar elementary storm is now called the polar magnetic substorm.

Since field-aligned currents had not been discovered until quite recently and due to the fact that ground-based magnetic observations cannot be used to obtain a unique causative current system, Birkeland's model was ignored for nearly a half century in favor of a purely ionospheric current system. Boström (1968) and Rostoker (1972a) have presented a detailed discussion of the controversies surrounding this particular topic.

During the past ten years, the idea of field-aligned currents has been revived, especially after satellite and rocket observations confirmed their existence (Cloutier, 1971), and now represent an integral part of the most recent models of substorm current systems (i.e., Boström, 1964; Boström, 1968; Atkinson, 1967; Akasofu and Meng, 1969; Meng and Akasofu, 1969; Bonnevier et al., 1970; Kamide and Fukushima, 1972; McPherron et al., 1973; Rostoker, 1974b).

Two "equivalent" current systems proposed to explain substorm fields are shown in Fig. 1. The current system in Fig. 1a (Sugiura and Heppner, 1965) is composed of an eastward electrojet in the evening sector, to explain the observed $+H$ perturbations in the evening sector, and a westward electrojet in the midnight and post-midnight sectors. Return currents for both electrojets consist of polar cap currents along with broadly distributed currents at lower latitudes. Kamide and Fukushima (1972) (Fig. 1b) have proposed a model three-dimensional current system containing both eastward and westward electrojets but with return currents flowing primarily along field lines (also see Kisabeth, 1972; Crooker and McPherron, 1972; Rostoker and Kisabeth, 1973). They have, however, also included small ionospheric return currents so as not to neglect their possible influence on low latitude geomagnetic variations. It should be emphasized that the parameters of both current systems in Fig. 1 can be adjusted to yield the same magnetic field variations on the surface of the Earth. In fact, Fukushima (1968, 1971, 1972) has demonstrated the equivalence of two- and three-dimensional current systems in detail, which is, of course, due to the non-uniqueness of current systems inferred from magnetic observations.

Even though various three-dimensional models have different closure paths in the magnetosphere (i.e., cross-tail current, ring current etc.), this fact will

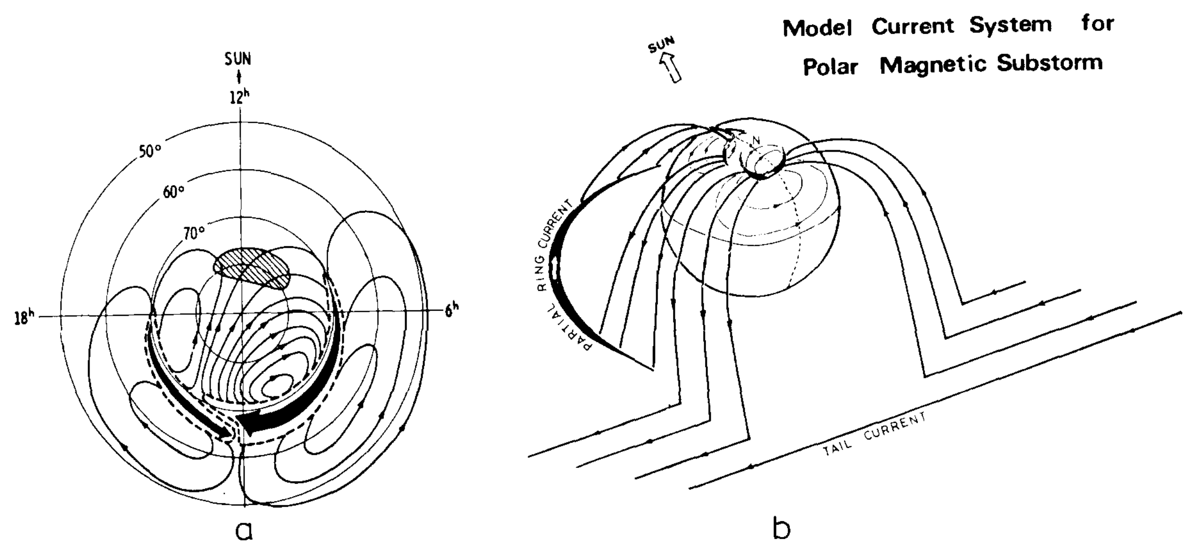

Fig. 1. a. Equivalent ionospheric current system involving a strong eastward electrojet in the pre-midnight sector along with a westward electrojet in the post-midnight sector (after Sugiura and Heppner, 1965).
b. Equivalent three-dimensional model for the eastward and westward electrojets. From ground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

not be of concern here because the primary contributions to substorm fields in and near the auroral zone are from field-aligned currents and electrojets. It should also be noted that model substorm fields at lower latitudes are due primarily to the field-aligned currents and not the closure currents in the magnetosphere. Field variations at lower latitudes due to various current systems are discussed in great detail in a recent review by Fukushima and Kamide (1973).

Field-aligned currents deduced from rocket and satellite observations are in the form of east–west-oriented sheet currents (Cloutier, 1971; Armstrong and Zmuda, 1973 and Chappell, 1974). These downward- and upward-flowing sheet currents are believed to penetrate the ionosphere all along the auroral oval, and are assumed to be connected in the ionosphere through north–south current flow, thus producing large toroidal magnetic fields in and above the ionosphere. Although these toroidal fields are large above the ionosphere, it is thought that their contribution to the total magnetic perturbation measured at the surface of the Earth is negligible (see Fukushima, 1971). However, this may not necessarily be the case (see Section 5e).

In this paper, the current systems producing these toroidal fields will be referred to as north–south (N–S) three-dimensional current systems, whereas the three-dimensional current systems containing the electrojets will be called east–west (E–W) three-dimensional current systems.

It also should be noted that, from an intensive study of the electrojets using magnetic field observations from satellites, Langel (1974a,b) has concluded that a sizable contribution to the Z component variations are of extraionospheric origin. This fact along with the existence of the large toroidal fields just discussed and the non-uniqueness problem, makes the study of causative current systems responsible for substorm fields extremely difficult.

3. Modelling substorm fields

Numerous numerical studies concerning the determination of magnetic fields associated with various three-dimensional model current systems have been reported in the literature (see Boström (1968) for a review of this subject), with the more recent being completed by Bonnevier et al. (1970), Boström (1971), Kamide and Fukushima (1971), Kawasaki and Akasofu (1971), Kisabeth (1972), Crooker and Siscoe (1974), Richmond (1974) and Kisabeth and Rostoker (1974b). Of these, only Boström (1971), Kisabeth (1972) and Kisabeth and Rostoker (1974b) have taken into account fields of induced currents in regions where large gradients in substorm fields occur (i.e., in the auroral zone).

Ashour (1971) derived a set of relationships between the components of the magnetic field of currents induced in the Earth and those of an external inducing field whose distribution is known numerically. For the case of an infinitely conducting Earth at some depth below the surface, Kisabeth (1972) and Kisabeth and Rostoker (1974b) have combined these relationships with the generalized form of the Biot-Savart law, thus yielding a simple matrix equation which gives the components of the total magnetic field (induced + external) due to an arbitrary volume distribution of current. This formulation has been applied successfully to various complex three-dimensional current systems (Kisabeth, 1972; Kisabeth and Rostoker, 1973; Rostoker and Kisabeth, 1973 and Kisabeth and Rostoker, 1974a). Also, magnetic fields due to current systems confined to the ionosphere can be calculated rapidly using this formulation.

Bonnevier et al. (1970) used a distribution of infinitesimal magnetic dipoles (current loops) along dipole field lines to obtain the scalar magnetic potential and thus the magnetic field associated with field-aligned currents. Using the same infinite conductivity model discussed previously, Boström (1971) applied the image dipole method directly to this distribution of magnetic dipoles in order to obtain the induced field.

Both methods have the advantage of having all the induction terms inside the volume integral over the source, hence they can be applied to complex current systems just as easily whether or not the induction field is taken into account. The added computer time required for computing the induced field amounts to less than 10% of the total. Therefore, a correction for induction in an infinitely conducting Earth is included on a routine basis.

Several researchers have simplified the problem of modelling electrojets (equatorial and polar) by using sheet or line current sources positioned horizontally over a flat Earth, along with image sources placed beneath an infinite conductivity layer (McNish, 1938; Forbush and Casaverde, 1961; Chapman, 1951; Walker, 1964; Scrase, 1967; Langel and Cain, 1968; Reimer, 1969; Heinrich et al., 1970; Czechowsky, 1971; Hanser et al., 1973). Forbush and Casaverde (1961) modelled magnetic field perturbations associated with the equatorial electrojet and found that a value of 250 km for the depth of an infinite conductivity layer yielded the best results. They also confirmed this to be true for auroral zone magnetic data published previously by McNish (1938). Kamide (1970) and Kamide and Fukushima (1970) have modelled both the polar electrojet and return currents confined to the ionosphere north and south of the auroral oval, but however, did not include the effects of induced currents.

Since the configuration of an E–W three-dimensional current system is controlled primarily by that of the Earth's dipole field, the physical parameters of the total system can be represented by those of the ionospheric segment alone. These generally include length (longitudinal extent), width (latitudinal extent), latitudinal current distribution across the polar electrojet, height of the ionospheric segment above the surface of the Earth and finally the latitude and longitude of the center of the current system. The longitude of the center is commonly referred to as the central meridian. Also, since the electrojet is known to flow along the auroral oval (Akasofu et al., 1965), auroral oval parameters have been included in the modelling of substorm fields (Kamide and Fukushima, 1970; Kisabeth, 1972; Kisabeth and Rostoker, 1974b).

Examples of how successfully substorm fields can be modelled using both two-dimensional and three-dimensional current systems are shown in Fig. 2. For the case of three-dimensional modelling (Fig. 2a), magnetic data recorded with the Canadian meridian (~302°) chain of stations during a polar magnetic substorm were used. The parameters for the model represented by the H, D and Z profiles are: width, 6.5° (~720km); length, 50°; central meridian, 315° (~13° east of the station line); total integrated current, 690,000 A (the current was assumed to be uniform across the electro-

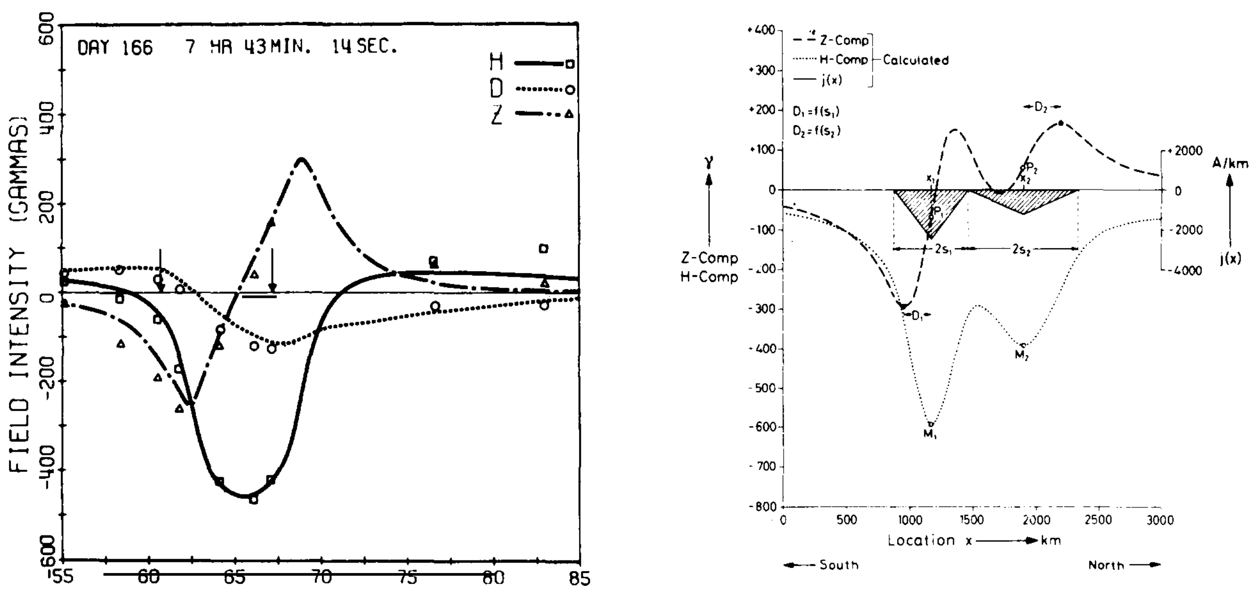

Fig. 2. a. Comparison of theoretical and observed profiles for a substorm commencing at 0702 UT on June 15, 1970. The observations were made with the Canadian chain of magnetometers. The arrows represent the boundary of the auroral oval along the central meridian of the three-dimensional model (after Kisabeth, 1972).
b. Profile of a two-dimensional model current system along with substorm field observations taken in the European sector. Note the existence of two distinct electrojets (after Czechowsky, 1971).

jet); height, 115 km and latitude of the center of the electrojet, 65°. The infinite conductivity layer was placed at a depth of 250 km in accordance with Forbush and Casaverde (1961) and Kisabeth (1972). Also, the ionospheric current was conformed to flow along the auroral oval, thus producing the deformation exhibited in the D component profile.

Note that in this example, the $+H$ regimes north and south of the auroral zone can be explained almost entirely by field-aligned currents rather than eastward-flowing return currents at high and low latitudes as depicted in Fig. 1a. There are, however, cases when a separate eastward electrojet must be introduced just south of the auroral zone in order to explain both the $+H$ regimes and the Z profiles. This is, of course, true in the region of the Harang discontinuity (see Rostoker and Kisabeth, 1973). It was fortunate that, in the case of the data shown in Fig. 2a, the eastward electrojet was far enough to the west of the line of stations that the substorm field could be treated with a single westward electrojet. Modelling substorm fields with both eastward and westward electrojets is presently being done by the author, utilizing generalized least-squares parameter estimation techniques and the large computing facility at the National Center for Atmospheric Research (NCAR).

Czechowsky (1971), using a two-dimensional ionospheric model, has been able to model substorm fields remarkably well with only limited data (four stations close to the same meridian). Fig. 2b shows an example of a double current system, he deduced by applying the Newton-Raphson iterative method to the field data. It is interesting to note that the average depth of the infinitely conductive layer obtained by Czechowsky is 450 km, considerably larger than the value of 250 km just discussed. This difference may possibly be explained by the fact that, since field-aligned currents produce a considerable $+H$ perturbation in the region between the down flowing and up flowing field-aligned currents while contributing very little to the vertical component, two-dimensional models require a larger depth for the image current system than that for three-dimensional models in order to obtain the same relative values between the H and Z components. Also, since the depth of penetration of substorm fields into the Earth is frequency dependent, the depth of the infinitely conductive layer used in modelling may have to be adjusted accordingly. This was indeed found to be the case when the depth of the superconductive layer was included as a parameter in a least-squares parameter estimation program (i.e., for a more rapidly changing current system, the depth to the superconductive layer was reduced). However, much more analysis must be completed before any conclusions can be formulated. One obvious difficulty encountered when using an infinitely conductive layer is that phase differences between internal and external fields are completely ignored. Nopper and Hermance (1974) have investigated this problem by using a simple two-layered Earth with various finite conductivities. Their results show that for a source like the polar electrojet, significant phase differences may occur.

Modelling the dynamic development of substorm fields using two- and three-dimensional models will be discussed in the next section.

4. Dynamic development of substorm fields

The fact that auroral and polar magnetic substorms are closely related has been known for quite some time (see Akasofu, 1968). In fact, the dynamic development of the polar magnetic substorm can be described within the framework of the auroral substorm as presented by Akasofu (1964) (Seiler and Kertz, 1967; Akasofu, 1968; Feldstein, 1969; Bonnevier et al., 1970; Kisabeth and Rostoker, 1971 and Kisabeth and Rostoker, 1974a.)

Recent advances in the study of dynamics of substorm fields have been brought about through the use of meridian chains of magnetometer stations. Using a meridian chain of stations in Europe, Bonnevier et al. (1970) have shown that magnetic field perturbation patterns from four isolated substorms can be explained by the development of E–W three-dimensional current systems. They found that a repetitive pattern was observed whereby the current system intensified and suddenly expanded northward (expansive phase) followed by a decay of the current system while moving equatorward (recovery phase).

Kisabeth and Rostoker (1971, 1974a) and Kisabeth (1972), using a meridian chain of stations in western Canada having both a high temporal and spatial resolution, were able to study the dynamic development of substorm fields in much greater detail than was possible with the previously existing network of stations.

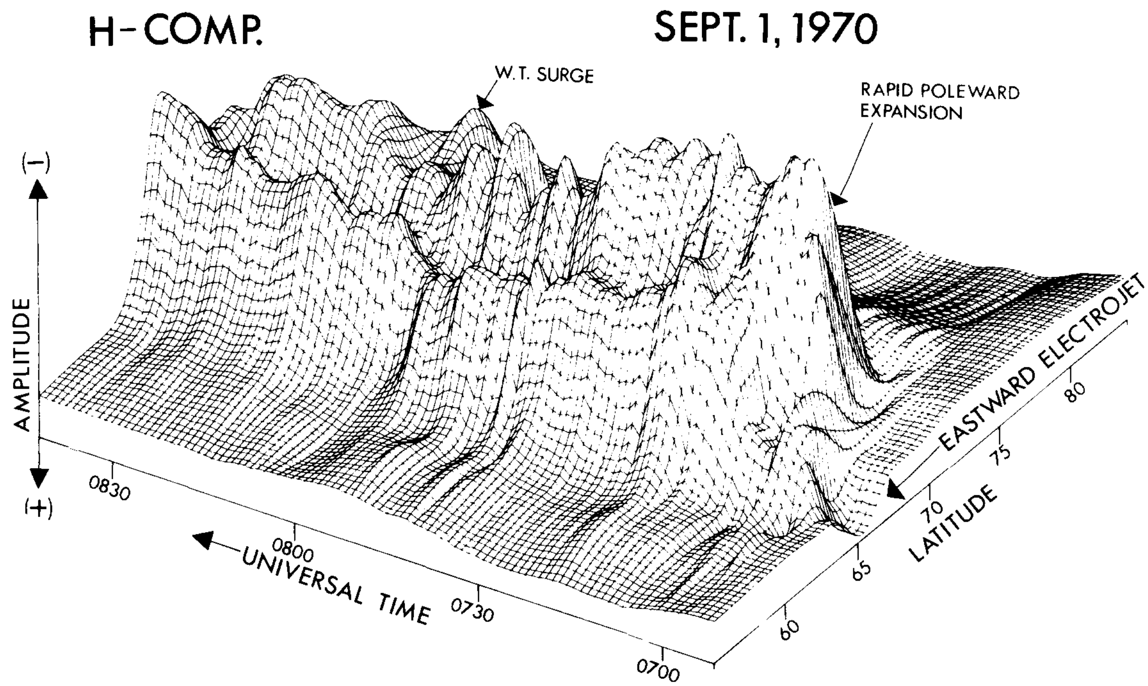

Fig. 3. Perspective view plot of the H component showing the dynamic development of a substorm that occurred on September 1, 1970. Note the stability of the southern border of the electrojet as compared with the northern border. The eastward electrojet appears as a depression or valley in this diagram prior to 0700 UT (after Kisabeth and Rostoker, 1974a).

The overall dynamic development of a substorm recorded with the Canadian chain of stations is illustrated by using a perspective view plot of the H component as shown in Fig. 3. The development of a double-current system, represented by the two mountain ranges, is clearly evident. Also, note the stability of the southern border of the electrojet as compared with the northern border activity. Three important morphological aspects of the expansive phase for this particular substorm are as follows:

(a) The moment of center of the current system moved rapidly poleward with a range in velocity of 280 m/sec (0656–0702 UT) to 1.6 km/sec (0702–0704 UT).

(b) The southern boundary of the electrojet remained relatively stable while the northern boundary moved poleward with an average velocity of 1.1 km/sec.

(c) The width of the electrojet expanded rapidly, reaching a value of 1,000 km by 0809 UT.

Kisabeth and Rostoker (1974a) further showed that the rapid growth of the auroral electrojet involves a series of steplike poleward jumps at the northern border of the current system. Wiens and Rostoker (1974) studied this in more detail and discovered that both the westward and poleward expansions take place through the sequential development of a series of westward electrojets which they have labeled a "substorm sequence".

It should also be mentioned that an east–west line of stations at mid-latitudes is being used to study substorm field developments (Clauer and McPherron, 1974). Using techniques developed by Zaitzev and Boström (1971), Clauer and McPherron have been able to successfully determine several parameters describing three-dimensional current systems along with following their dynamic development.

Another way to study the dynamic development of a substorm is by using various parameter estimation techniques. Fig. 4a shows the latitudinal current distribution as a function of time obtained by Czechowsky (1971). The theoretical latitude profile previously discussed (Fig. 2b) is for 0130 UT. It is interesting to note the similarities between the development of this substorm and that shown in Fig. 3.

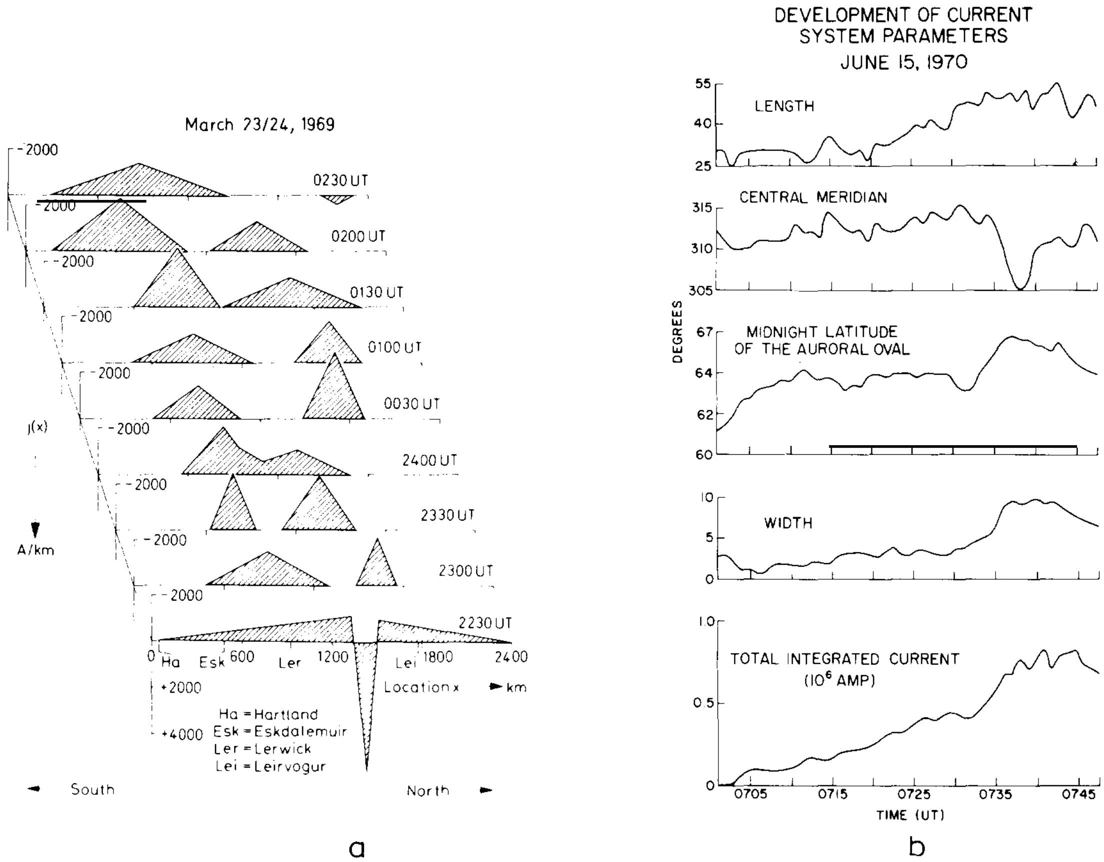

Fig. 4. a. Latitudinal current distribution derived using an iterative method to fit a model ionospheric current system with magnetic variations recorded during a substorm (after Czechowsky, 1971).
b. Parameter variations showing the development of a substorm in terms of an equivalent three-dimensional current system. Note the rapid expansion of the current system at 0735 UT (after Kisabeth and Mareschal, 1974).

Kisabeth and Mareschal (1974) were able to apply the method of generalized least-squares parameter estimation in order to obtain the various current system parameters for the three-dimensional current system discussed in the last section. A sample of the results showing the temporal development of the various parameters is given in Fig. 4b. The height of the current system and depth of the infinitely conducting layer were set at 115 km and 250 km respectively. These parameter variations depict a dynamic development that agrees extremely well with that reported in a previously published analysis of this particular substorm (see Kisabeth and Rostoker, 1971). The large intensification of the current system at 0733 UT was due to the development of the northern border of the electrojet. Also, the central meridian moved rapidly westward, thus indicating an addition of a new current system to the north and west of the previously existing current system, in complete agreement with Wiens and Rostoker (1974). A maximum current flow of 823,000 A was reached at 0740 UT.

It should be pointed out that the analysis of this particular substorm required 75,000 integrations over complex three-dimensional current systems, but was accomplished rapidly using the matrix formulation described in the previous section along with the computing facility at NCAR.

5. Some suggestions for future research

Although excellent progress has been made in the study of substorm fields since Birkeland's pioneering work at the turn of the century, many problems are still open to investigation. Some of these problems, which this author feels are important, are as follows:

(a) More permanent magnetic observatories are desperately needed in both hemispheres. Also, as Gough (1974) has pointed out, some of the existing stations should be moved because of anomalous measurements due to lateral inhomogeneities in the subsurface conductivity structure. Furthermore, using existing knowledge of well-defined current systems, new station locations should be chosen so as not to contribute totally redundant data. A study could possibly be made using generalized inverse techniques on synthetic magnetograms (generated by hypothetical current system developments), in order to determine what station positions contribute the most valuable information. For example, it may possibly be shown that a given number of stations positioned along a magnetic meridian provides much less information about the causative current system than does a random, x or cross type distribution utilizing the same number of stations. However, such a study would depend heavily on knowing what is a well defined current system. The present knowledge of current system configurations in existence during various phases of polar magnetic substorms is limited. The proposed high-resolution magnetometer network to be installed as part of the International Magnetospheric Study (IMS) should greatly enhance this knowledge. Nevertheless, the probable cut back in the number of magnetometer stations after the completion of the IMS program may require such a study as just suggested in order to determine which stations would be more valuable for monitoring substorm current systems in the future (see below).

(b) Real-time analysis of magnetic data from selected observatories in the northern and southern hemispheres should be attempted, using two- and three-dimensional models along with various least-squares parameter estimation techniques. The real-time parameter changes could be used to locate and track the eastward and westward electrojets. This would provide much needed information for ionospheric forecasting, rocket launches etc. Records of such current-system parameters depicting the dynamic development of eastward and westward electrojets would also supplement AE (auroral electrojet) indices, and in fact, may prove to be far superior. Although the number of parameters and stations would have to be large for tracking these current systems, Heinrich et al. (1970) and Hanser et al. (1973) have already succeeded in real-time analysis using two magnetometers and assuming the electrojet to be a line current. The problems of using three-dimensional current systems, along with induced currents in a spherical Earth, would definitely compound the situation. Even so, this author believes that the solution to this particular problem will be developed in the near future.

(c) Further work should be done to determine the effects of finite conductivity on substorm fields, especially in the auroral zone (see Goodwin et al., 1973; Hibbs and Jones, 1973; Nopper and Hermance, 1974). Also, rather than using purely ionospheric sources (two-dimensional), three-dimensional current systems such as that shown in Fig. 1b should be included in the finite conductivity problem.

(d) The configuration of the current system in the immediate vicinity of the westward travelling surge should be investigated in more detail (see Akasofu et al., 1965; Meng, 1965; Atkinson, 1967; Mende et al., 1972; Kisabeth and Rostoker, 1973). This investigation will depend heavily on the finite conductivity problem mentioned above due to the fact that currents are changing so rapidly, both temporally and spatially.

(e) Leakage of toroidal magnetic fields from N–S current systems with extensive longitudinal extent should be examined in detail. Both, variations in the longitudinal distribution of field-aligned current flow and possible shears in the sheet currents could cause significant magnetic fields at the surface of the Earth. Since sheet currents exist all along the auroral zone, substorm activity, especially the westward-travelling surge and the poleward motion of the auroral bulge, obviously could create such conditions. Kisabeth (1972) has shown that shears can cause perturbation patterns on the ground which appear as though the development of an eastward or westward electrojet has taken place; eastward or westward depending upon the sense of shear and direction of current flow in the original N–S current system.

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