AN INVESTIGATION OF POLAR SUBSTORMS OBSERVED AT HALLEY BAY, ANTARCTICA

by

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Abstract

Ground observations of magnetic and ionospheric substorms are reviewed, and the processes involved are explained. Then magnetic and absorption results from an auroral zone station, Halley Bay, are examined. Positive H bays occur in the evening sector between 16.00 and 22.00 local time while negative H bays occur on the nightside between 22.00 and 06.00 local time. Clockwise and counterclockwise rotating Pi2 pulsations respectively have similar times of occurrence, as do westward and eastward moving radio aurora. Short-period absorption occurs coincident with magnetic bays while longer-period absorption occurs on the dayside (04.00 to 20.00 local time). This information is used to determine the disturbance pattern in local time seen at auroral zone stations.

A simple model is presented to illustrate the processes responsible for the effects observed in the 3 different local-time zones. On the nightside there is direct injection of particles from the tail, into the ionosphere, accompanied by short-circuiting of the cross-tail current through the ionosphere to produce the westward electrojet. Protons are injected into the radiation belt on the evening side, and their westward drift constitutes a partial ring current. The plasmasphere bulge modifies the distribution of proton precipitation and influences the location of the ionospheric return current, the eastward electrojet. Trapped electrons drift into the morning and dayside sectors and precipitate steadily into the ionosphere producing periods of slowly-varying absorption. The diurnal and seasonal variations of this

absorption at Halley Bay suggests that photodetachment of negative ions in the D region is a significant factor in the production of auroral absorption.

It is shown that variations in fxI significantly affect the occurrence of blackout on the ionoscnde, making this an unreliable indicator of absorption.

Anomalies in the magnetic bays observed at Halley Bay are shown to be due to the presence of induced currents in the sea flowing parallel to the continental shelf.

An analysis of electrical power system disturbances identifies magnetic substorms as the primary cause, and discusses how knowledge about substorms can aid prediction of the power system disturbances.

CONTENTS

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PREFACE

Geomagnetic storms have been the cause of disturbances on man-made systems since the last century (see review by Lanzerotti, 1978), but technological improvements over the years have reduced the impact of geomagnetic storms on most of the systems. The electric power distribution network, however, with the tendency toward higher voltage lines and more inter-connected systems, is becoming more, not less, susceptable to disturbance during geomagnetic storms (see Appendix C on 'The Problem of Solar Induced Currents'). Thus there is an urgent practical need for a greater understanding of the geomagnetic disturbances observed on the ground. This thesis presents an analysis of ground observations of polar substorms, one of the fundamental components of a geomagnetic storm.

1. INTRODUCTION

This thesis has its origins when the author was running the ionospheric programme at Halley Bay, a geophysics observatory in the Antarctic. Curiosity about the disturbances seen on the records prompted comparison between the magnetometer, ionosonde and riometer records; which revealed that disturbances often occurred simultaneously on all the records. The disturbances were accompanied by bright auroral displays and usually also meant a loss of radio contact with the outside world. All these apparently unrelated phenomena (ie. magnetic disturbances, radio wave absorption, and aurora) are different aspects of polar substorms, and their cause can be traced back to an explosive process (called a magnetospheric substorm) in the tail region of the earth's magnetic field.

The opportunity to study in Canada, with Dr. T. Watanabe at U.B.C., allowed the author to further investigate polar substorms. Substorms occupy a central position in space physics as they are the fundamental process by which energy from the solar wind is transfered into the earth's atmosphere. Also investigations of the substorm processes in the earth's magnetosphere are at the frontiers of research in plasma physics. Substorms also have considerable effects on the ground; an investigation of electrical power system problems identified magnetic substorms as the source of the disturbances; also ionospheric substorms are responsible for disruptions in H.F. radio communications.

Many theories have been proposed to account for magnetic and ionospheric substorms, but over the years a generally accepted picture of substorm processes has evolved. The purpose of this thesis is to test this substorm picture against the data collected by the author at Halley Bay. Shortcomings in the present substorm picture, revealed by this study, are then investigated and new theories suggested.

1.1 What Is A Substorm?

Geomagnetic storms have certain reccgnised features, such as a depression of the field strength at low latitudes lasting several hours, and shorter (approx 1 hour) changes in the field strength at high latitudes. The latter feature was termed a "polar magnetic substorm" by Chapman(1935) and is now recognised as the fundamental component of a magnetic storm. Ionospheric disturbances accompanying these magnetic substorms have been similarly labelled ionospheric substorms, and are characterised by anomalous icnization in the lower ionosphere which is responsible for increased absorption of high frequency radio waves.

It is believed that when the interplanetary magnetic field (IMF) turns southward there is a greater interaction between the solar wind and the magnetosphere. The energy accumulated in the magnetosphere as a result seems to be released in a succession of explosive prccesses (termed magnetospheric substorms) involving acceleration of particles in the magnetospheric tail towards the earth. These particles injected from the tail are guided by the field lines and precipitate, directly or indirectly, into the ionosphere in the north and south auroral zones. This precipitation gives rise to the magnetic and ionospheric effects that constitute polar substorms.

1.2. Halley Bay

Halley Bay is situated on the Brunt Ice Shelf on the coast of the Weddell Sea (fig 1). The station was established by the Royal Society as a geophysics observatory for the International Geophysical Year (IGY, 1957/8) and is now run by the British Antarctic Survey.

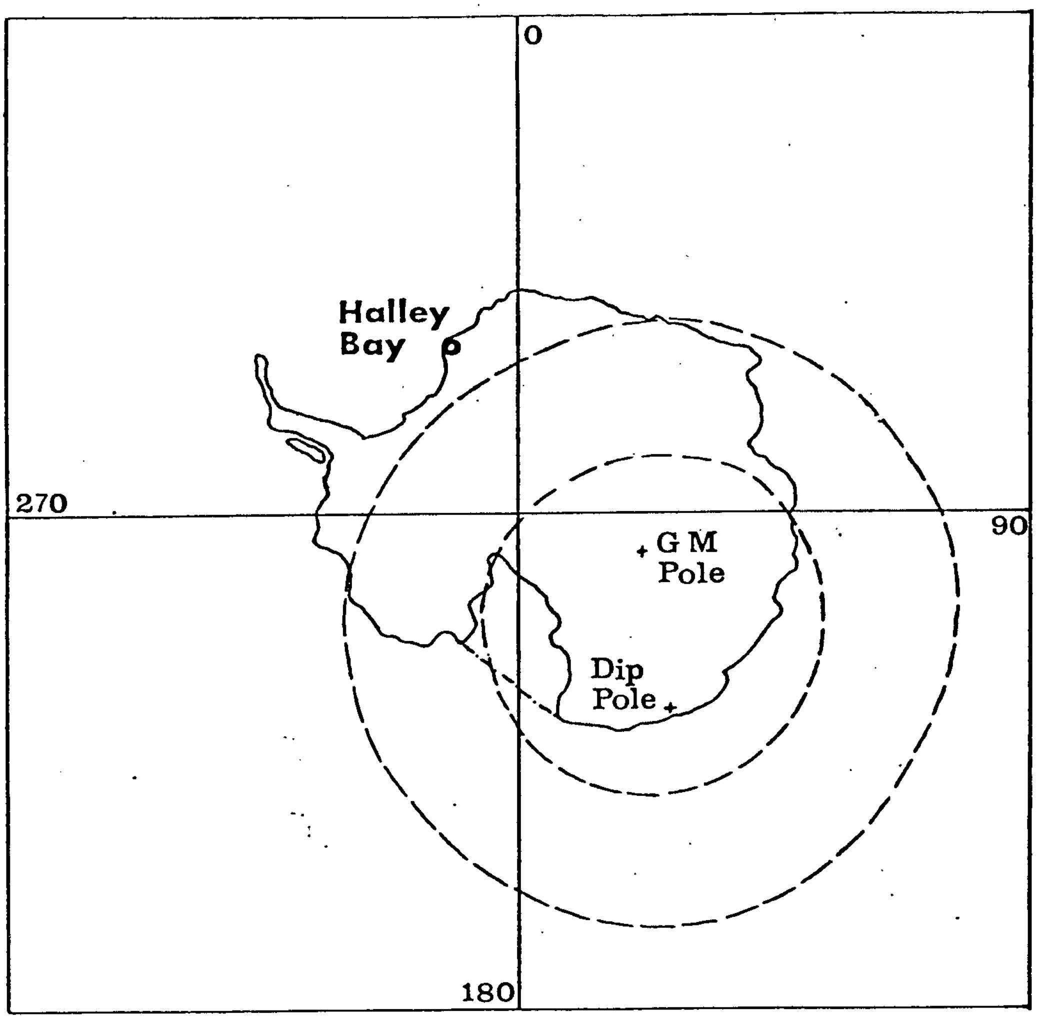


Fig. 1. Map of Antarctica showing the location of Halley Bay, together with the mean position of the austral auroral zone as reported by Bond and Jacka (1960, 1962). Co-ordinates are geographic longitude.

The characteristics of ground observations of polar substorms are determined by the distribution of the precipitation from the magnetosphere and by the characteristics of the ionosphere and its response to that precipitation. The particle precipitation occurs along the auroral zone (which is roughly centred around the invariant pole) and so has a dependence on invariant latitude. Ionospheric characteristics, however, are controlled by the intensity of incident solar radiation and so exhibit a dependence on geographic latitude.

At quiet times the auroral oval is south (poleward) of Halley Bay, however during disturbed periods the auroral oval moves equatorward and passes over the station. This makes the station an ideal place for studying storm effects along the auroral oval and for examining phenomena with an auroral zone distribution. Also Halley Bay is at a uniquely high geographic latitude for an auroral zone station (ie. compared to its invariant latitude - see table 1). Thus it is particularly suited to differentiate between phenomena with a geographic and an invariant latitude dependence and hence determine whether they are controlled by solar radiation or by magnetospheric effects.

Geographic	Latitude	75.5° South
	Longitude	333.4° East
Geomagnetic	Latitude	65.8° South
	Longitude	24.6° East
L-shell value at 400km altitude		4.6
L-shell value at surface		4.2
Invariant Latitude (Surface)		60.9°
Geocentric Dip		-64.3°

Local zone or W30 mean time, LZT = UT - 2hours

Local magnetic time (July 15, 1972), MLT = UT - 3hours ± 20min.

Table 1. Co-ordinates of Halley Bay.

1.3. Outline Of The Thesis

This thesis deals with two aspects of polar substorms: magnetic substorms, and the ionospheric substorms characterised by auroral absorption.

First, to illustrate the presently accepted substorm picture, a survey is made of key results presented by other authors. Chapter 2 is concerned with magnetic substorms and presents a summary of ground based observations and explains how these can be used to determine the distribution of electric currents responsible. This provides a full description of the spatial characteristics of the magnetic disturbances. The electric-circuit approach of Bostrom (1972) is used to explain the temporal variations of the disturbances. Chapter 3 describes the morphology of the auroral absorption and considers reports of a day/night asymmetry in the ratio of absorption to the flux of precipitated electrons responsible. Theories of the precipitation mechanism involved are also considered.

The next two chapters feature an analysis made by the author of substorm features observed at Halley Bay, principally using data personally collected by the author. Chapter 4 presents a detailed analysis of magnetic bays and Pi2 pulsations observed at Halley Bay, and comparison is also made with observations of radio aurora. These phenomena occur during night hours and all show different behaviour before and after 22.00 local time. This is shown to be in agreement with the picture of eastward and westward electrojets seperated by the Harang discontinuity. Chapter 5 details the absorption results from Halley Bay, including both the rapidly varying absorption that is coincident with magnetic bays, and the slowly varying absorption that occurs on the dayside. The results support the view of Hartz and Brice (1967) that seperate classes of 'splash' and 'drizzle' precipitation are responsible for the absorption observed.

The Discussion in chapter 6 examines the substorm picture developed by other authors by using the Halley Bay results obtained by the author. As a result of this a new unified picture of substorm features is developed. Comparison between the Halley Bay results and the 'prevailing' substorm picture presented in chapters 2 and 3 reveal two areas of confusion: the cause of the eastward electrojet and the role of photodetachment with regard to auroral absorption. Both these points are examined and possible explanations of these features are proposed.

In the course of this study several important results have been established, which have been submitted or accepted for publication, and are contained in appendices. A comparison between the riometer and ionosonde techniques of measuring absorption (Appendix A) shows that variations in fxI seriously affect the occurrence of blackout on the ionosonde, making this an unreliable indicator of enhanced absorption.

An earlier study (Appendix B) of the azimuth of disturbing vectors responsible for the magnetic bays at Halley Bay revealed the presence of induced currents in the sea, and for the first time demonstrated their effect on magnetic bays in the D component.

A topical review of substorm effects on electric power systems is presented in Appendix C, and the factors affecting the severity of power system disturbances are discussed. Knowledge about substorm characteristics is used to suggest ways of predicting power system disturbances.

2. MAGNETIC SUBSTORMS

2.1. Ground Observations Of Magnetic Bays And Pulsations

A magnetic bay is simply a departure of the magnetic field strength from its quiet time level and is generally accepted as the signature of a magnetic substorm. Magnetic bays are usually characterised by an increase (or decrease) of the field strength to a peak (or trough) in 15 to 30 minutes, followed by a more gradual decrease (or increase). Magnetic bays are observed at night (22.00 to 06.00 local time) and in the H component have a positive sign at mid latitudes and a negative sign at high latitudes. In addition positive H bays are sometimes observed at high latitudes in the evening sector (16.00 to 22.00 local time). The signs of bays in the Z component in the midnight-morning sector are generally positive (downward) north of the auroral oval and negative to the south, with the signs reversed in the evening sector. These features are well documented (Akasofu, 1968) and are attributed to a line current in the ionosphere flowing along the auroral oval, westward in the midnight-morning sector, eastward in the evening sector. However bays in the D component are not so easy to explain and a consistent picture of their behaviour is yet to emerge. In a statistical study of bays observed at Scandinavian stations, Harang (1946) showed that negative bays in H were usually accompanied by an eastward deflection in D, while later workers (eg Akasofu and Meng, 1969) found cases where the D deflection was to the east in the late evening sector but to the west in the morning sector.

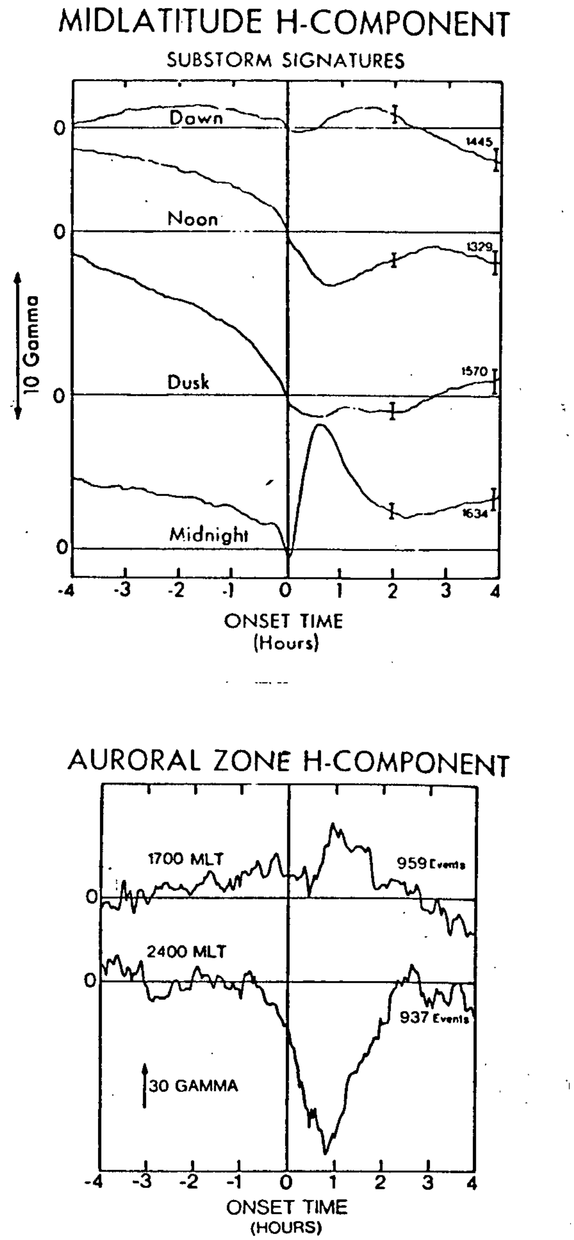


Fig. 2. Substorm signatures in the H component obtained by Caan et al (1978): a) at midlatitudes, b) in the auroral zone

Identification of a substorm from magnetic records by using the criteria above is still rather subjective. However recently Caan et al (1978), using a computer pattern-recognition program, analysed 1800 substorm events and determined the statistical magnetic signature for different latitudes and local times. They identified the time of a substorm onset by the occurrence of a positive H bay at a mid-latitude station, within ± 5 hours of station local midnight. For the onset times so determined, the magnetic records from many locations were analysed and, with a superposed-epoch technique, used to determine characteristic substorm signatures for different local times. The substorm signature in the mid-latitude H component is shown in fig 2a while that in the auroral zone H component is shown in fig 2b.

Shorter period variations than magnetic bays are termed pulsations. Pulsations are classified as continuous (Pc) or irregular (Pi) and each group is further subdivided according to frequency as shown in table 2 (see Jacobs, 1970, for further details). Pi2 pulsations occur principally in the night-time auroral zone and frequently occur coincident with magnetic bays (see fig 8) sc will be included in this investigation. The observed polarization characteristics indicate that Pi2 pulsations cannot be described by a simple equivalent current system such as that used to describe a bay. Such a current system provides an in-phase relationship between the H and D components which is not observed to be the case (Jacobs 1970). The dominant rotation, counterclockwise in the north and clockwise in the south, suggests that Pi2 are subject to propagation effects and they are commonly attributed to an oddmode oscillation of dipole field lines. Such an oscillation would give a conjugate relationship in which the H variations were in phase and the D variations were out of phase. However such a relationship was also found by Campbell (1971) for the magnetic bays observed at the conjugate stations Great Whale River and Byrd.

	Period (sec)	Magnitudes (γ)
Pc1	0.2 - 5	0.05 - 0.1
Pc2	5 - 10	0.1 - 1
Pc3	10 - 45	0.1 - 1
Pc4	45 - 150	0.1 - 1
Pc5	150 - 600	1 - 10
Pi1	1 - 45	0.01 - 0.1
Pi2	45 - 150	1 - 5

Table 2. Classification of continuous pulsations (Pc) and irregular pulsations (Pi), (after Jacobs, 1970).

2.2. Equivalent Current Systems

Extensive studies have been made of the pattern of magnetic bays in order to determine the complete current system responsible (see review paper by Anderson and Vondrak, 1975). To examine the distribution of a magnetic disturbance it is more convenient to represent magnetic bays by an equivalent disturbing vector which represents the amplitude and orientation of the total disturbance of the component bays. The observed distribution of disturbing vectors is then often expressed in terms of an equivalent current system in the ionosphere (fig 3) which, as Akasofu (1968) pointed out, is a mathematically correct method of representation. This should not be confused, however, with models of the actual current system for, as Chapman (1935) stated, it is not possible to determine uniquely the current system from ground observations alone.

The equivalent current system shows an intense westward current along the auroral oval, called the auroral electrojet, together with return currents spread equatorward of this and over the polar cap. (Some authors have suggested that the current system should include an eastward electrojet, to the west of the main electrojet, to account for bays in the evening sector.) Such a configuration was postulated for the actual current system by Chapman (1935) and Vestine and Chapman (1938). An alternative current system featuring field-aligned currents was suggested by Birkeland (1908) and Alfven (1939), (see fig 4).

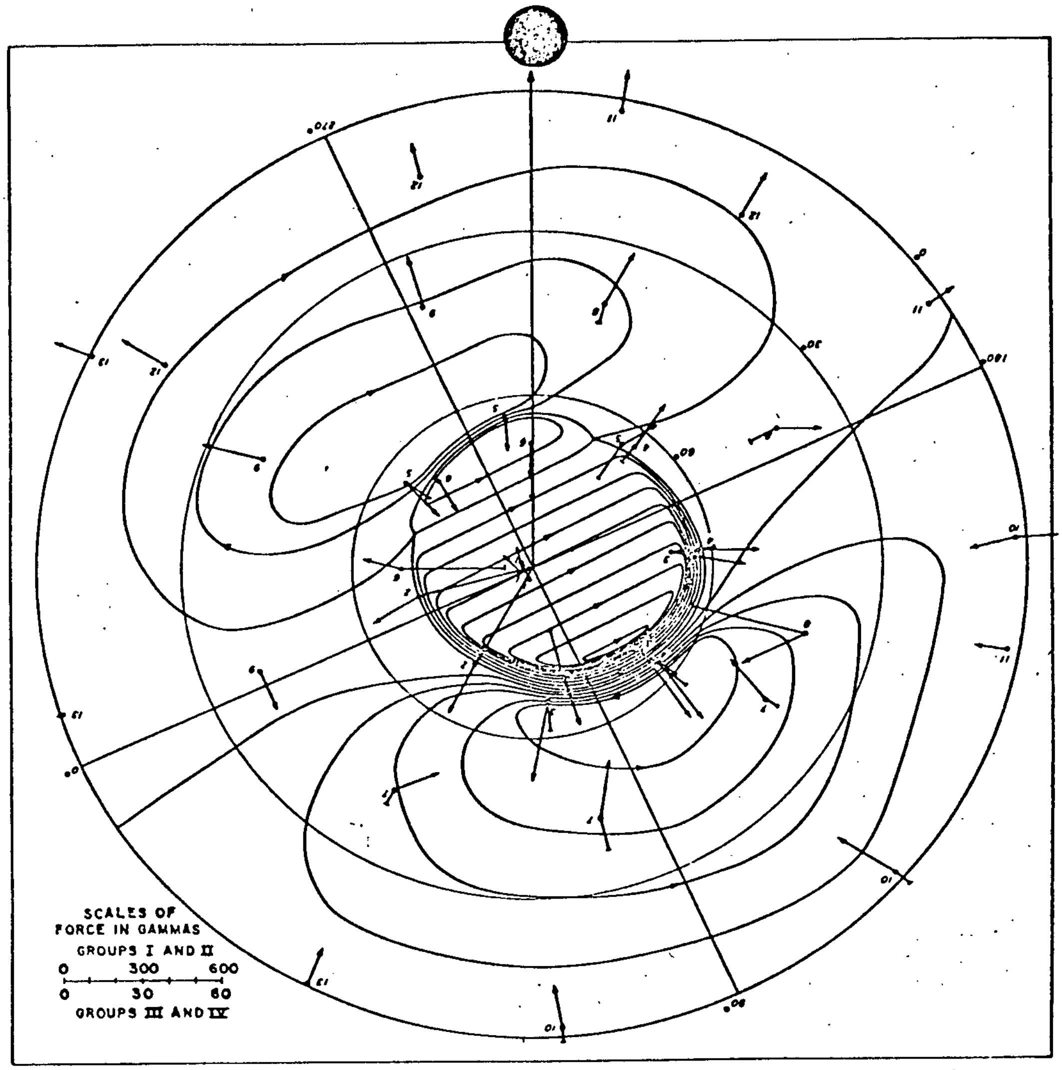


Fig. 3. The distribution of the magnetic disturbance vectors and the equivalent current lines which corresponds to the average for many bays (Silsbee and Vestine, 1942).

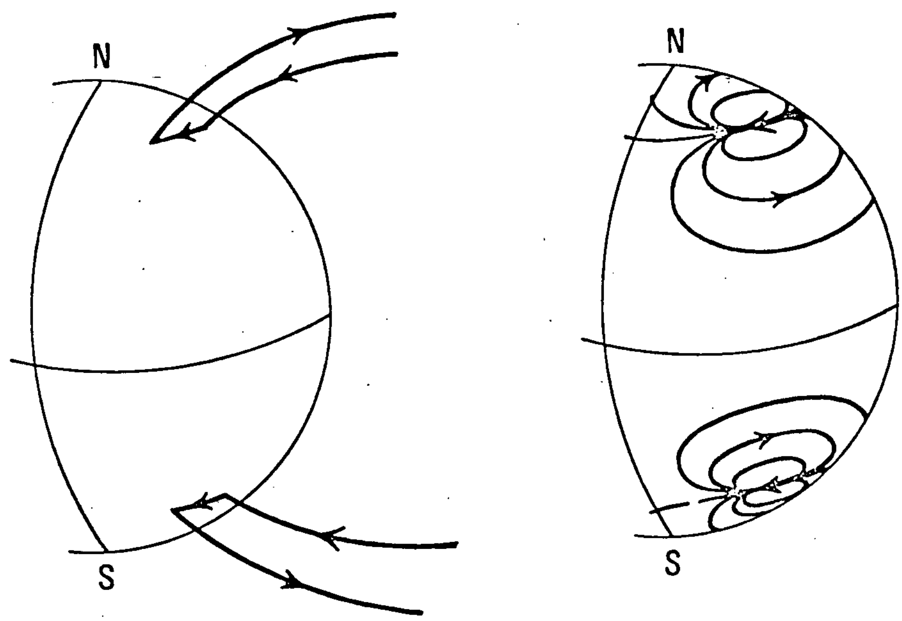


Fig. 4. Current systems proposed to account for polar magnetic substorms. Note that the currents occur simultaneously in both hemispheres. a) shows the Birkeland - Alfven system which features field-aligned currents. b) shows the purely ionospheric Chapman - Vestine current system.

The two current systems were compared by Fukushima (1969). The Birkeland-Alfven system can be considered as the superposition of the Chapman-Vestine system and two vertical currents each combined with horizontal spreading. Fukushima has shown that a vertical current in the magnetosphere combined with horizontal spreading produces no magnetic effect below the ionosphere. In consequence the Birkeland-Alfven and Chapman-Vestine systems are equivalent in terms of the magnetic bays they produce on the ground.

More recently, satellite observations (Heikkila and Winnington, 1971; McPherron et al, 1973; Yasuhara et al, 1975) have provided evidence that the actual current system involves field-aligned currents. It has also been shown (Zmuda and Armstrong, 1974) that downward and upward field-aligned currents always appear as a pair on opposite sides of the auroral oval. If the emf is of magnetospheric origin the westward electrojet can be explained as a Hall current, along the auroral oval, set up as the result of a strong equatorward electric field (and Pederson current) across the auroral oval (fig 5). Alternatively an ionospheric emf can be used to account for the field - aligned currents. Fukushima (1971) demcnstrated that a westward electric field wculd produce a primary Hall current with a pattern similar to that of the Sq system. When this is combined with enhanced conductivity along the auroral oval there is a space charge accumulation along the edges of the auroral oval. The resulting electric field would produce a secondary Hall current that would flow westward along the auroral oval and return via the ionosphere. Pederson currents across the oval and field aligned currents would be produced as a by-product and would represent leakage of the space charge. Such a current system is represented in fig 6 (after Fukushima, 1971) and Fukushima emphasised that the systems involving magnetospheric or ionospheric emfs produce the same magnetic disturbance pattern on the ground. However they produce different magnetic effects above the ionosphere so it will be possible to identify the correct current system using satellite observations.

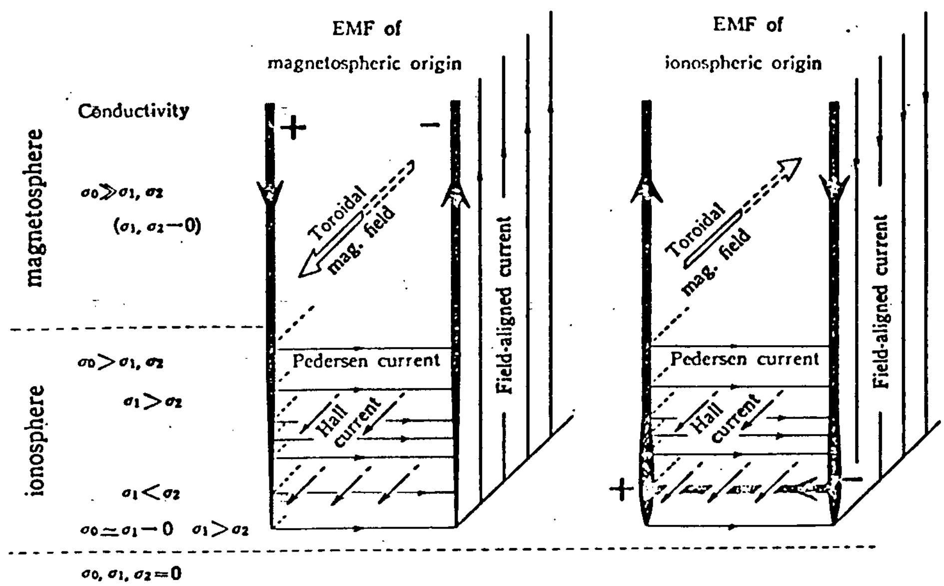


Fig. 5. Meridional cross-section of the three-dimensional current flow and toroidal magnetic field when the electromotive force is of magnetospheric origin (left) and of ionospheric origin (right), after Fukushima (1971)

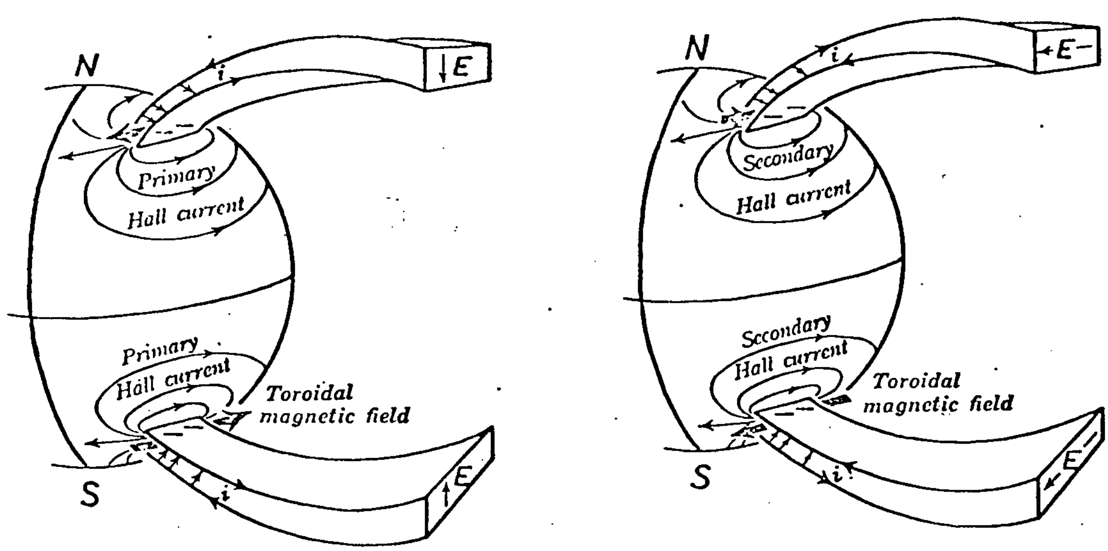


Fig. 6. Toroidal magnetic field in and above the auroral zone ionosphere associated with the meridianal field-aligned current (after Fukushima, 1971).

2.3. Latitude Profile Of Substorms

Much useful information about the auroral electrojet can be obtained from simultaneous magnetic observations at a chain of stations, on a magnetic meridian, extending across the auroral zone. Such a chain in Canada has been extensively used for electrojet studies (eg Kisabeth and Rostoker, 1977) and this section will examine some of the results obtained. However initially it is useful to consider the theoretical latitude profile (fig 7) computed by Kisabeth (1972) for a current system featuring a westward electrojet connected to field-aligned currents as shown in fig 4a.

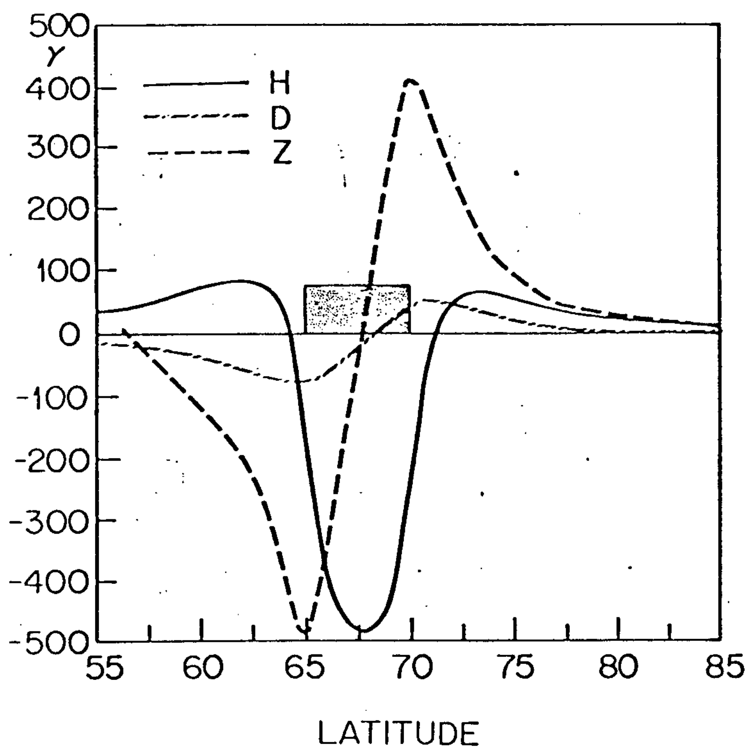


Fig. 7. Theoretical latitude profile of the magnetic disturbance in the H, D, and Z components, produced by a three-dimensional current system featuring a westward electrojet connected to field-aligned currents. (Kisabeth, 1972).

Fig 7 shows the characteristic substorm features: a negative H disturbance at auroral latitudes with a positive H disturbance at lower latitudes and in the polar cap; and a reversal of the Z disturbance immediately below the electrojet. Kisabeth (1972) also reported that the D bay configuration is determined by whether the meridian of the latitude profile is east or west of the central meridian of the current system. Magnetic records, from the Canadian chain, for a substorm on 14th July 1970 are presented in fig 8a which shows the magnetic bays and fig 8b which shows the simultaneous occurrence of Pi2 pulsations. Latitude profiles of the three components for different stages of the substorm are shown in fig 9. Fig 9c shows latitude profiles similar to the theoretical profile of fig 7, however fig 9d shows a noticeably different profile and examination of other results showed that there are considerable dynamic changes to the electrojet system within the course of a typical substorm.

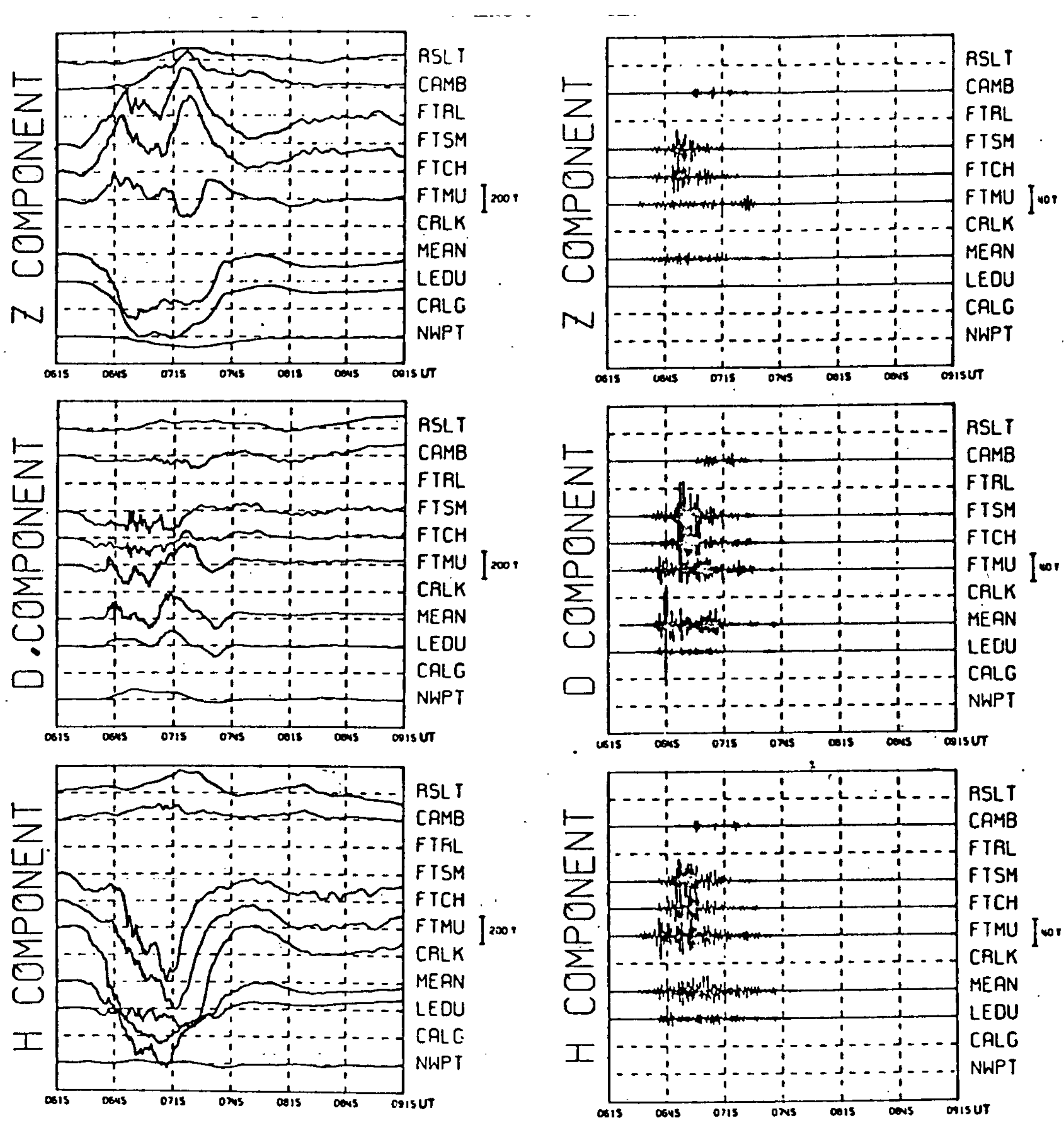


Fig. 8. Magnetic bays and Pi2 pulsations recorded by the Canadian chain of magnetometers during a substorm on July 2, 1970 (Kisabeth and Rostoker, 1977).

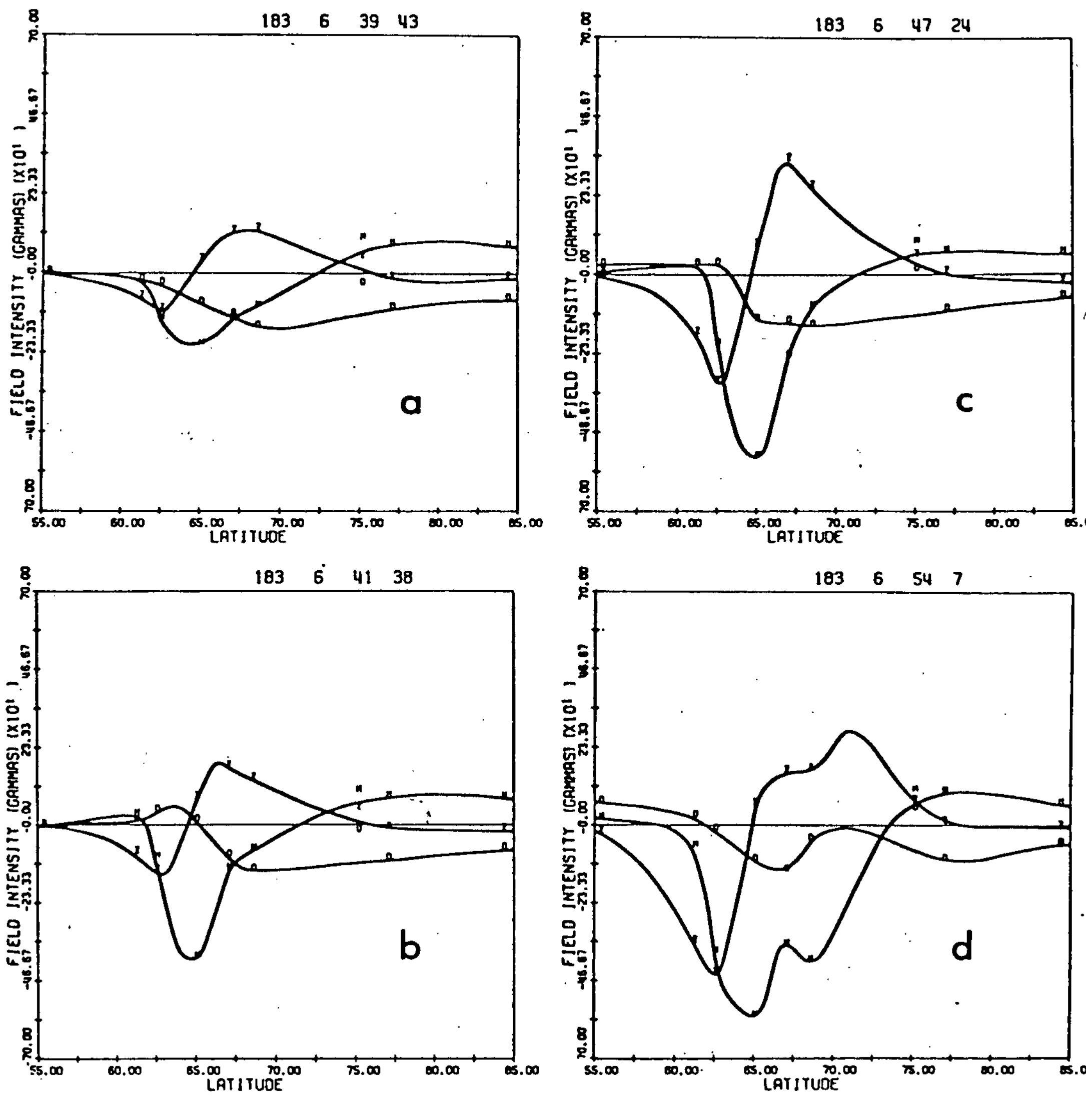


Fig. 9. Latitude profiles for 4 times during the substorm on July 2, 1970, shown in fig 8.

The application of inversion theory to the electrojet problem by Oldenburg (1976,1977) has provided a more sophisticated technique for interpreting magnetic records from a chain of stations. Solution of the inverse problem involves the manipulation of a suite of ground-based data to infer ionospheric and magnetospheric current densities within the framework of a specific curren geometry. Inversion of magnetic variations during a substorm on 15th July 1970 by Oldenburg (1976), assuming the current system shown in fig 6a, indicated that the magnitude of the westward current density was at least 0.90±0.15 A m^{-1} and that the current density could not be approximated by a constant value over widths much greater than 1 degree of latitude.

Inversion techniques were also used to analyse the magnetic field values at the Canadian chain of stations during quiet times. A study by Hughes et al (1978) showed that eastward and westward electrojets exist in the evening and morning sectors respectively even when no substorm activity could be detected. This is of considerable significance for, as Hughes et al pointed out, it implies that similar current systems exist both as a steady state feature and a disturbed feature which would indicate that the substorm is a perturbation of a pre-existing current pattern.

2.4. Circuit Diagrams Of The Substorm Ctrrent System

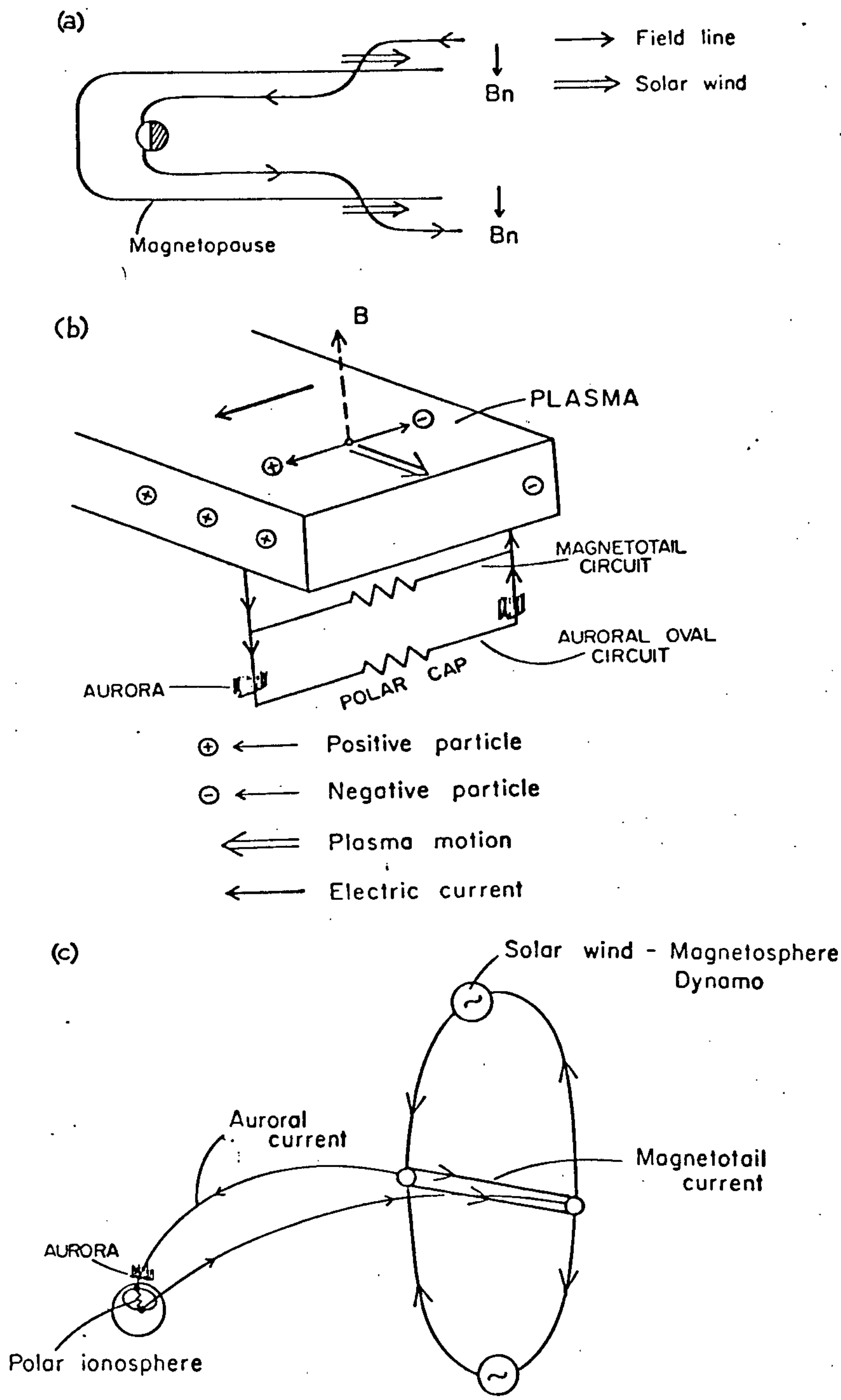
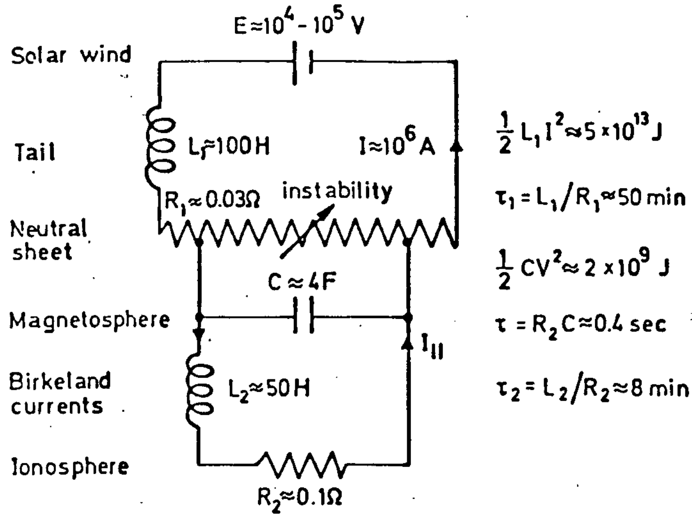


Fig. 10. Schematic diagram showing the magnetospheric processes and current systems that give rise to the electrojet in the auroral oval, and consequently magnetic substorms.

The primary energy source for magnetospheric processes, including the substorm current system, is the interaction between the solar wind and the flanks of the magnetosphere. This interaction can be considered as a dynamo which drives a current across the central region of the magnetotail (see fig 10). During substorms an increase in the resistance of the magnetotail circuit causes the current to flow down field lines, around the auroral oval, and back up field lines to the tail. Falthammar and Bostrom (Bostrom, 1972) developed a circuit for the substorm current system defined entirely by lumped circuit components, as shown in fig 11a. Energy is stored in the magnetospheric tail in the form of magnetic energy and as kinetic energy of plasma motion. The magnetic energy can be directly represented by an inductance while the kinetic energy is analogous to the energy stored in a capacitor. The magnetotail current is estimated to be about 10^6A so to account for the energies released during substorms (typically 10^{13} to 10^{14} Joules) would require an L value of 100 Henrys which would give a stored energy value, $0.5LI^2$, of 5×10^{13} Joules. The kinetic energy of the plasma sheet has been estimated at 2×10^9 Joules and to represent this energy by a capacitor (where $E = 0.5CV^2$) charged to 3×10 volts would require a capacitance of 4 Farads.



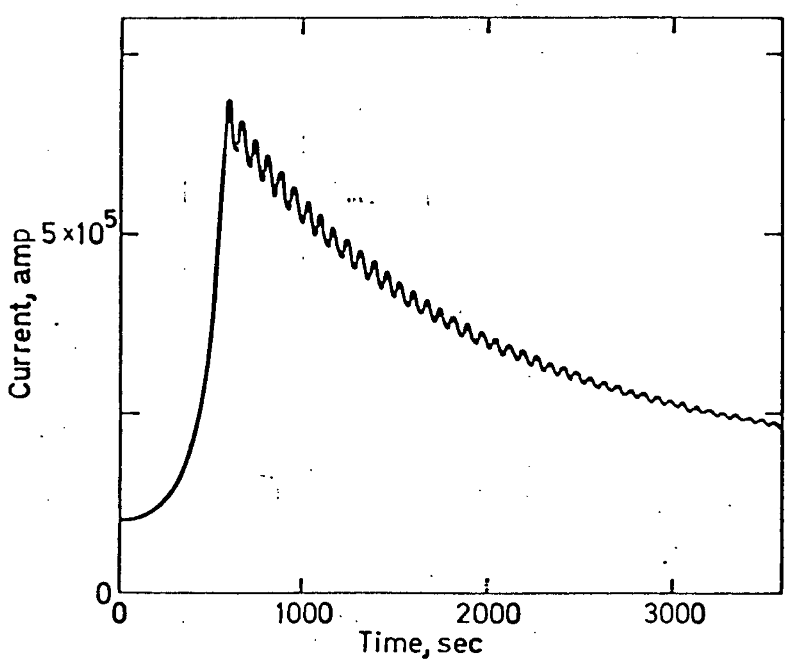


Fig. 11. a) equivalent circuit for the substorm current system.
b) time variations of the current to the ionosphere (Bostrcm, 1972).

At the onset of a substorm the tail resistance is postulated to increase so that the current must flow through the ionospheric resistor and the inductance due to the increased dimensions of the circuit. Bostrom (1968) suggested values of 0.1 ohm and 50 henrys for these components which would give a time constant for the growth of the electrojet current, L/R, of 8 minutes which is consistent with the observed rapid onset of bays. The capacitance of 4 farads has little effect on the gross development of the electrojet current, but combined with the L and L of the electrojet circuit causes oscillations with a period of about 70 seconds. This value is typical of the period of Pi2 pulsations which frequently accompany magnetic bays. The decay of the electrojet current is associated, by Bostrom (1972), with the time constant of the magnetotail circuit, $L/R \approx 50$ minutes. The temporal variations of the current through the ionosphere resistor, caused by a sudden increase in tail resistance, are shown in fig 11b. An actual electrojet with such temporal characteristics would certainly be consistent with most ground magnetic observations during substorms.

3. IONOSPHERIC SUBSTORMS

Abnormal absorption can be subdivided into Polar-Cap Absorption (PCA), Sudden Cosmic Noise Absorption (SCNA) and Auroral Absorption (AA) (Hultquist, 1966). PCA events cover the polar cap as well as auroral latitudes and are produced by energetic protons (Bailey, 1964). SCNA events extend to lower latitudes and the magnitude of the absorption is related to the solar zenith angle (Holt, 1963). Both SCNA and PCA events are seen rarely in sunspot minimum years (Hultquist, 1966; Piggott and Hurst, 1976) and are disregarded in this study which is concerned with auroral absorption.

It is generally accepted that auroral absorption is produced by electron precipitation. The incoming electrons also produce bremsstrahlung X rays which themselves produce ionization and hence absorption. This contribution to the total absorption, however was found by Hultquist (1966) to be an order of magnitude less than that due to electrons with E<5keV and as this is itself less than the absorption produced by higher energy electrons, the bremsstrahlung-produced absorption can be regarded as negligable.

Observations of bremsstrahlung X ray energy can, however, be used to provide information about the energy of the electron precipitation; and using such measurements Bewersdorff et al (1966) showed that the average energy of precipitated electrons is between 30keV and 50keV. This agrees with the results of Jelly et al (1964) who found a good correlation between the distribution of auroral absorption and electron fluxes of E>40keV. These electrons are of higher energy than those producing visual aurora (Ansari, 1964) and so will penetrate deeper into the ionosphere than the height at which aurora are usually seen (100km or above). Bailey (1957) has shown that electrons with energies of 30-50keV will produce ionization between 80 and 100km. Rocket measurements of electron density during polar substorms at Syowa Station, Antarctica, show significant ionization down to 70km (fig 12 after Nagata et al, 1975).

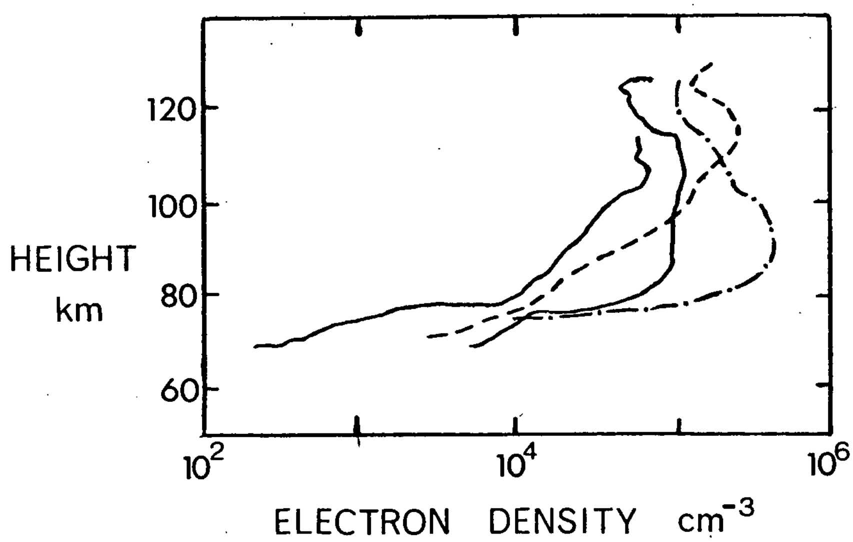


Fig. 12. The vertical profiles of electron density above Syowa station during 4 polar substorms (Nagata et al, 1975).

3.1. Morphology Of Auroral Absorption

On the nightside, auroral absorption extends to lower latitudes than the auroral arcs and electrojet with which it is associated (Nagata et al, 1975), but its temporal variation is the same as that of magnetic bays. The extent of the absorption is shown by results from the Canadian chain of stations, reported by Jelly (1970), (fig 13).

Dayside absorption, however has different characteristics which will be outlined in this section. The distribution of absorption recorded at a north-south chain of stations in Canada had a maximum at 08.00 geomagnetic time (Hartz et al, 1963). Comparison with similar results from Norwegian stations shows that the two patterns were comparable in geomagnetic time but not in local time.

The seasonal variation of absorption, that Hultquist (1966) quotes as typical of auroral zone stations, features a maximum in winter and minimum in summer. However the seasonal variation of auroral blackout, reported by Collins et al (1961) shows a peak occurrence in the equinoxes at all geomagnetic latitudes up to 80°. An examination of the individual stations in the work of Hartz et al (1963) shows that at Ottawa and Val d'Or most absorption occurred in the autumn whereas at the higher latitude stations, Cape Jones and Churchill, absorption was most frequent in the winter. Thus reports of the diurnal variation of absorption are reasonably consistent but, as yet, there is no clear picture of the seasonal variation.

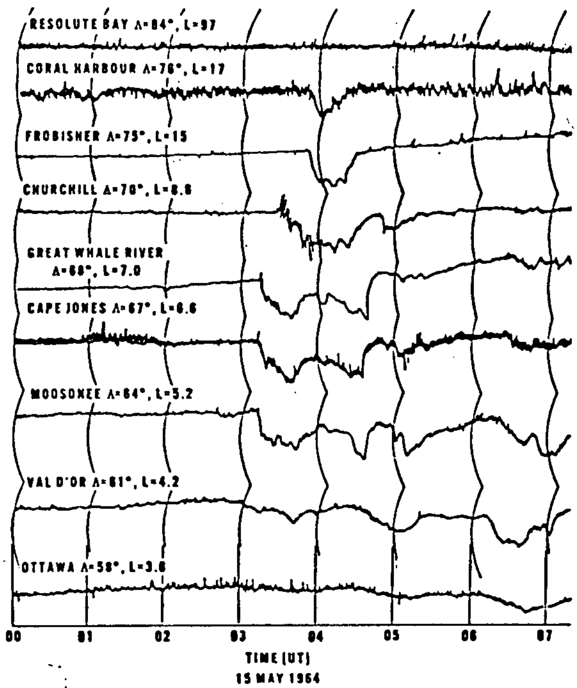


Fig. 13. Absorption recorded by the Canadian north-south chain of riometers during a substorm on May 15, 1964 (Jelly, 1970).

A complete survey of absorption produced by substorms at stations round the whole of the northern auroral zone was made by Berkey et al (1974). They produced synoptic maps of absorption for 60 substorms from IQSY (1964-1965) and IASY (1969) and found that in the majority of cases the absorption region expanded eastward during a substorm, as shown in fig 14. The rate of expansion, on average, corresponded to the drift velocity of electrons with energies 50-300 keV, but the variability of the expansion rate suggested that other processes, apart from simple longitudinal drift, might be involved. As well as the eastward motion, in about half the substorms examined, Berkey et al also found evidence of a simultaneous westward motion of the absorption region into the evening sector. This work finally confirmed that dayside absorption was related to polar substorms. However the observed variations in dayside absorption cannot be explained simply by precipitation due to scattering of drifting electrons; and Berkey et al (1974) proposed that either changes in the response of the ionosphere to precipitation must occur, or that an independent precipitation mechanism is involved.

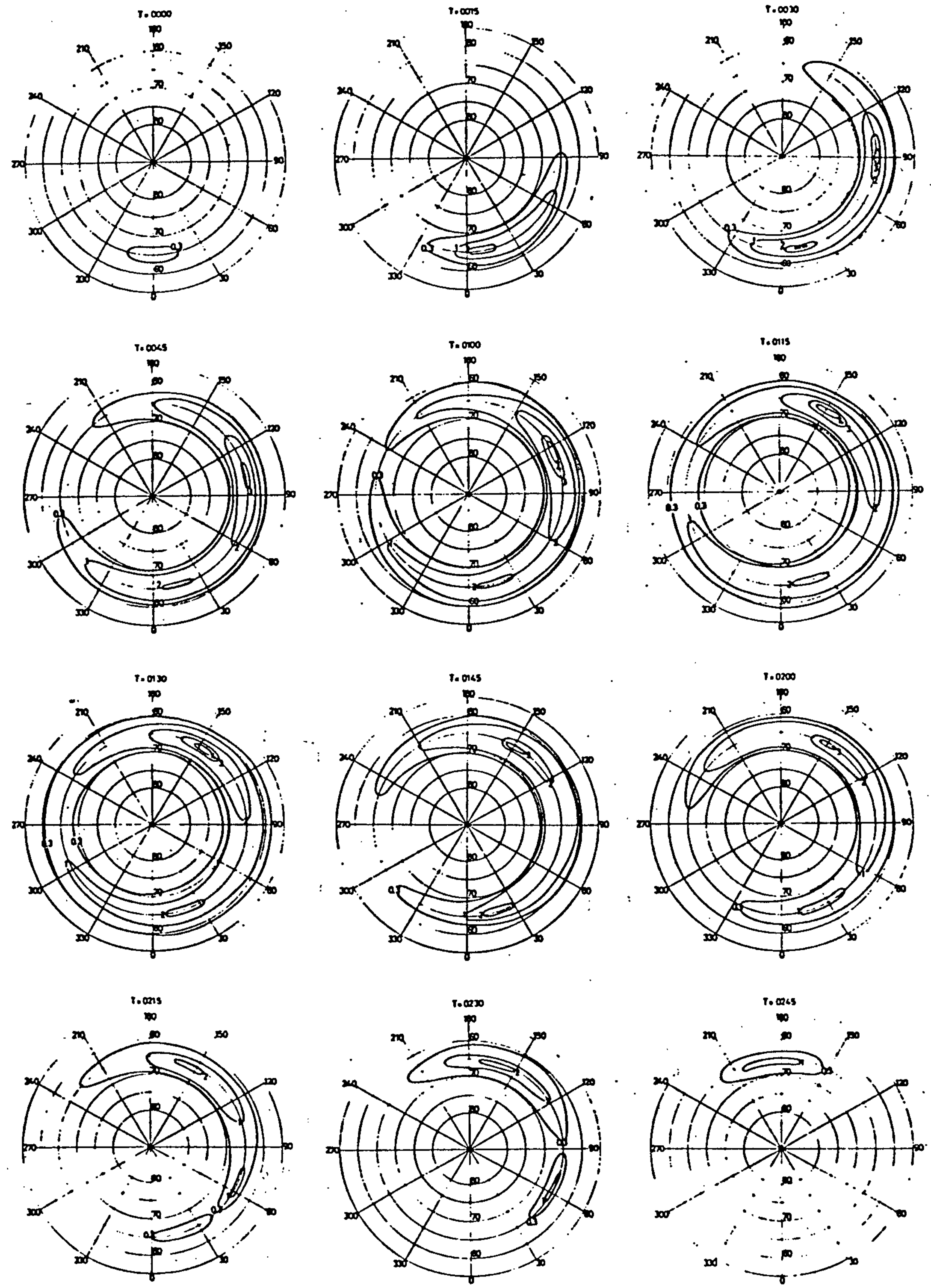


Fig. 14. The average temporal development of the auroral absorption associated with 60 substorms studied by Berkey et al (1974). The coordinate system is one of corrected geomagnetic latitude and time.

3.2. Response Of The Ionosphere To Precipitation

Measurements of auroral absorption and the causative precipitated flux of electrons with E>40keV responsible for it have been compared by Jelly et al (1964). They derived an average relationship between the two and found that the same flux produced twice as much absorption during the day as at night. That is

In daytime $A = 2.6 \cdot 10^{-3} \cdot J^{1/2}$

In night-time $A = 1.3 \cdot 10^{-3} \cdot J^{1/2}$

where A is absorption in dB and J is electron flux in cm^{-2} sec^{-1} $sterad^{-1}$. This day/night asymmetry may be due to either differences in the energy spectrum of the precipitated electrons or changes in the ionosphere.

Evidence for a variation with local time in the precipitated electron spectra was found by Bewersdorff (1966) from measurements of the energy of bresstrahlung X rays. Differences of the electron spectrum have also been reported by Parks et al (1968).

Changes in the ionosphere have been indicated from models of the D region proposed by various authors, eg Bailey (1957), Zmuda and Potemra (1972). According to these models a significant process is the loss of electrons by attachment to neutrals to form negative ions. During the night this reduces the electron density but during the day the electron density is restored because there is photodetachment of the electrons by sunlight: this will affect absorption values; and riometer measurements during PCA events have indicated day-night ratios between 3 and 6 (Reid, 1969). Ionospheric changes were also suggested by Saito et al (1974) as an explanation for the day/night asymmetry of absorption at Syowa. However Hultquist (1966) claims that photodetachment is negligable for auroral absorption and Berkey et al (1974), in their study of auroral absorption, found no effect produced by the absorption region moving between the day and night sectors, so the problem is still controversial.

3.4. Precipitation Mechanisms

The electrons involved in precipitation into the dayside ionosphere arrive by longitudinal drift from the nightside. Direct measurements during substorms of electrons with energy>30keV have been made by the ESRO 1A satellite (Smith and Thomas, 1976) which showed that counts of trapped electrons have a maximum coincident with maximum magnetic substorm activity, on the nightside, but, on the dayside, have a maximum 1-2 hours later than maximum substorm activity.

Trapped electrons spiral round field lines and bounce back and forth from one end of the field line to the other, the mirror height depending, inter alia, on their pitch angle. Hence collisions of electrons which alter their pitch angle can result in their precipitation (pitch angle diffusion). Other processes which alter the pitch angle of the electrons will also result in their precipitation, for instance electron cyclotron instability. This involves a resonance effect whereby kinetic energy of the electrons is transferred to wave energy which can be detected as VLF emissions. Only energy from the transverse component of the electron velocity is transferred so the process results in a change of the electron pitch angle with the consequent increased probability of precipitation (see Kennel and Petschek, 1966, for rigorous treatment of electron cyclotron instability).

Pulsations are also believed to be related to precipitation of trapped electrons since satellite measurements have shown that fluctuations in electron counts in the radiation belt often coincide with certain types of micropulsation. McPherron et al

(1968) found that, in the local time period 02.00 to 10.00, Pi1 pulsations correlated with 5-10 second period fluctuations of electrons with energy>15keV. In the local time period 10.00 - 15.00, Pc3 pulsations correlated with 20-40 second period fluctuations of electrons with energy > 30keV. When micropulsations and electron fluctuations occur simultaneously significant energy is present in the common frequency band. McPherron et al (1968) concluded that a causal relationship between the pulsations and the modulated electron precipitation was a definite possibility. They argued that due to the more continuous nature of the pulsations these would have the fundamental role in such a relationship.

More recently, Southwood (1974) has shown theoretically that pulsations can be generated by the Kelvin Helmholtz instability at the surface of the magnetosphere. These pulsations set up oscillations of the field lines inside the magnetopause and these oscillations propagate down the field lines. These waves are reflected back at the lower boundary of the magnetosphere and when the field line path length is an exact multiple of the micropulsation wavelength a resonance condition occurs. Normally the energy for resonance is fed in from the instability at the magnetopause but the energy can also be derived from trapped electrons. Such coupling of electrons to field line oscillations may result in precipitation of the electrons into the ionosphere and consequent production of enhanced absorption.

Also, Sato(1965) found a correlation between fluctuations in absorption at College, in the northern auroral zone, and Pc5 pulsations observed at both College and Macquarie Island, in the southern auroral zone (fig 15).

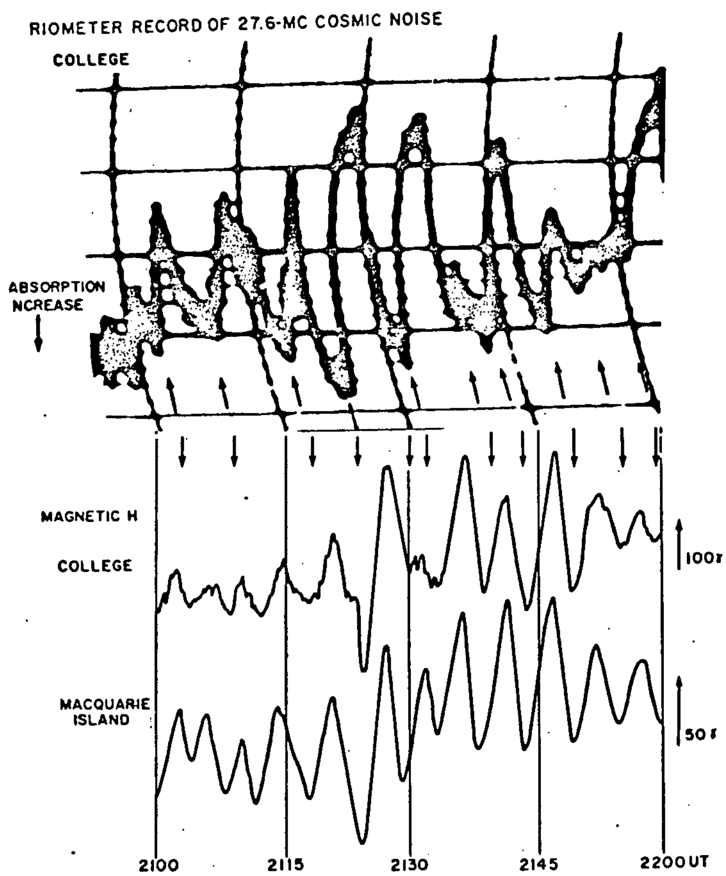


Fig. 15. Auroral absorption at College, Alaska, and Pc5 pulsations recorded at College and Macquarie Island in the southern auroral zone (Sato, 1965).

4. MAGNETIC OBSERVATIONS AT HALLEY BAY

This section presents an analysis of the magnetic bays noted by the author at Halley Bay during 1974 and 1975. Comparison is also made with magnetic disturbances at Halley Bay during the IGY, reported by MacDowell and Blackie (1961). Data on Pi2 pulsations is also presented (after Hamilton, 1979) together with a comparison made by Green and Hamilton (1978) of Pi2 pulsations observed at Halley Bay and its conjugate point, St. Anthony. Also included is a study of radio aurora at Halley Bay by Shipstone (1971).

4.1. Magnetic Bay Results

Magnetic bay disturbances were identified from the recordings of a fluxgate magnetometer. The only criteria for selection of bays from amongst other disturbances were whether the bay was clear enough for a start time to be determined as well as an amplitude and duration measured. In consequence there is a bias in the results towards bays recorded during magnetically quiet conditions. Measurements were made of the magnitude of the disturbance in the H, D and Z components ΔH, ΔD and ΔZ, and the results grouped according to the sign of the disturbance (see table 3).

Of 294 bays studied 222 are contained in group A for which typical values of disturbance are $\Delta H = 365\gamma$, $\Delta Z = 275\gamma$ and $\Delta D = 260\gamma$. This group of bays occurred between 22.00 and 06.00 local time, ie roughly centred about magnetic midnight (01.00 local time) whilst bays in group B occurred between 16.00 and 21.00 local time (fig 16). Bays in group C occurred during

Group	Sign of Disturbance			Percent of Total
	H	Z	D	
a)	-	+	+	71.1
	-	+	-	4.4
b)	+	-	+	0
	+	-	-	16.3
c)	-	-	+	1.7
	-	-	-	6.5
d)	+	+	+	0
	+	+	-	0

Table 3. Frequency of magnetic bays in 1974-75, classified according to the sign of the H and Z disturbances. A total of 294 bays are included, recorded between January 1974 and December 1975.

both the evening and night-time periods, though those with a negative bay in the D component occurred principally in the evening period, whilst those with a positive D bay occurred in the night-time period. Each magnetic bay disturbance was analysed to define the angle of azimuth (tan $\Delta D/\Delta H$) and the angle of elevation (tan $\Delta Z/\Delta H$) of an equivalent disturbing vector.

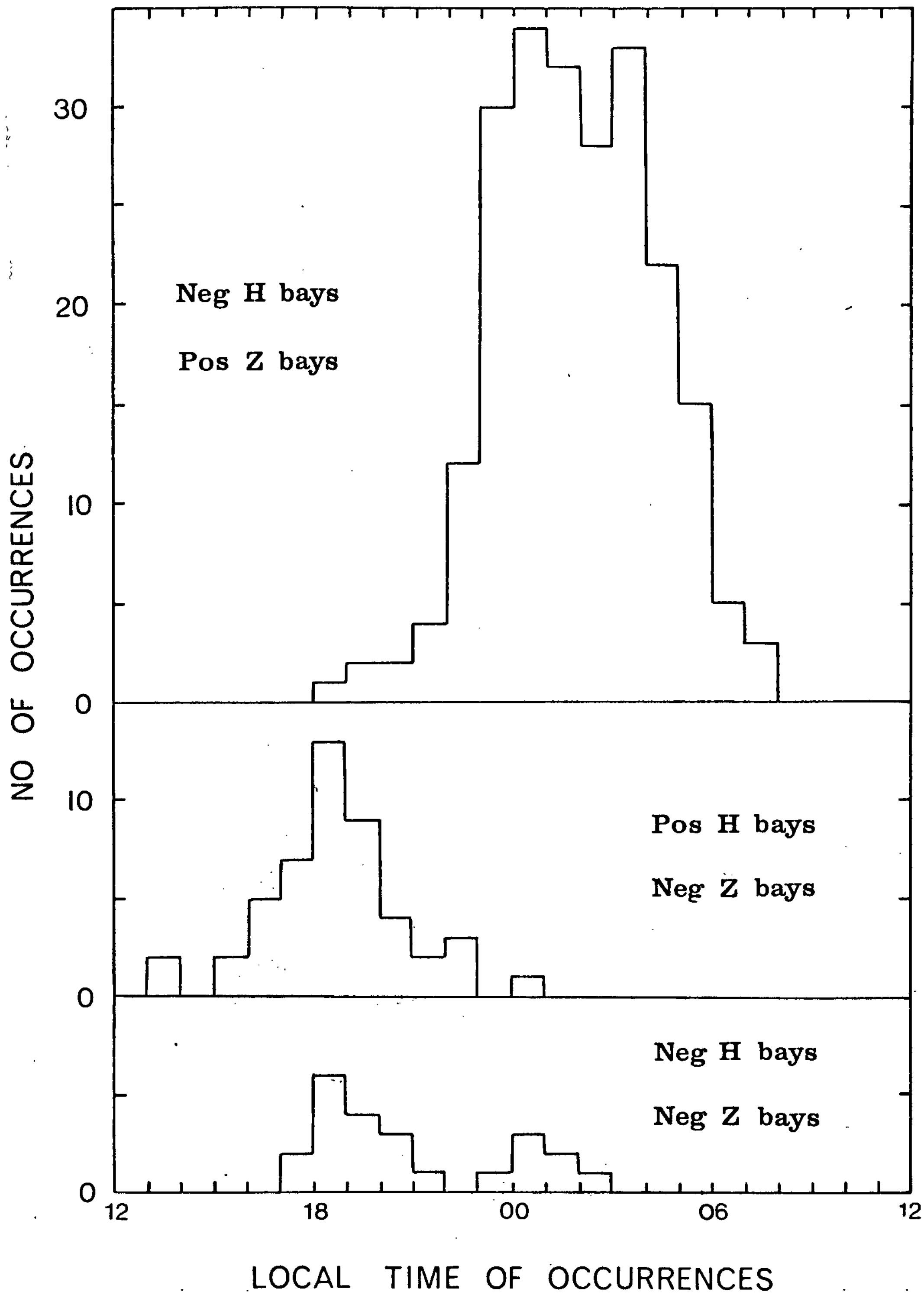
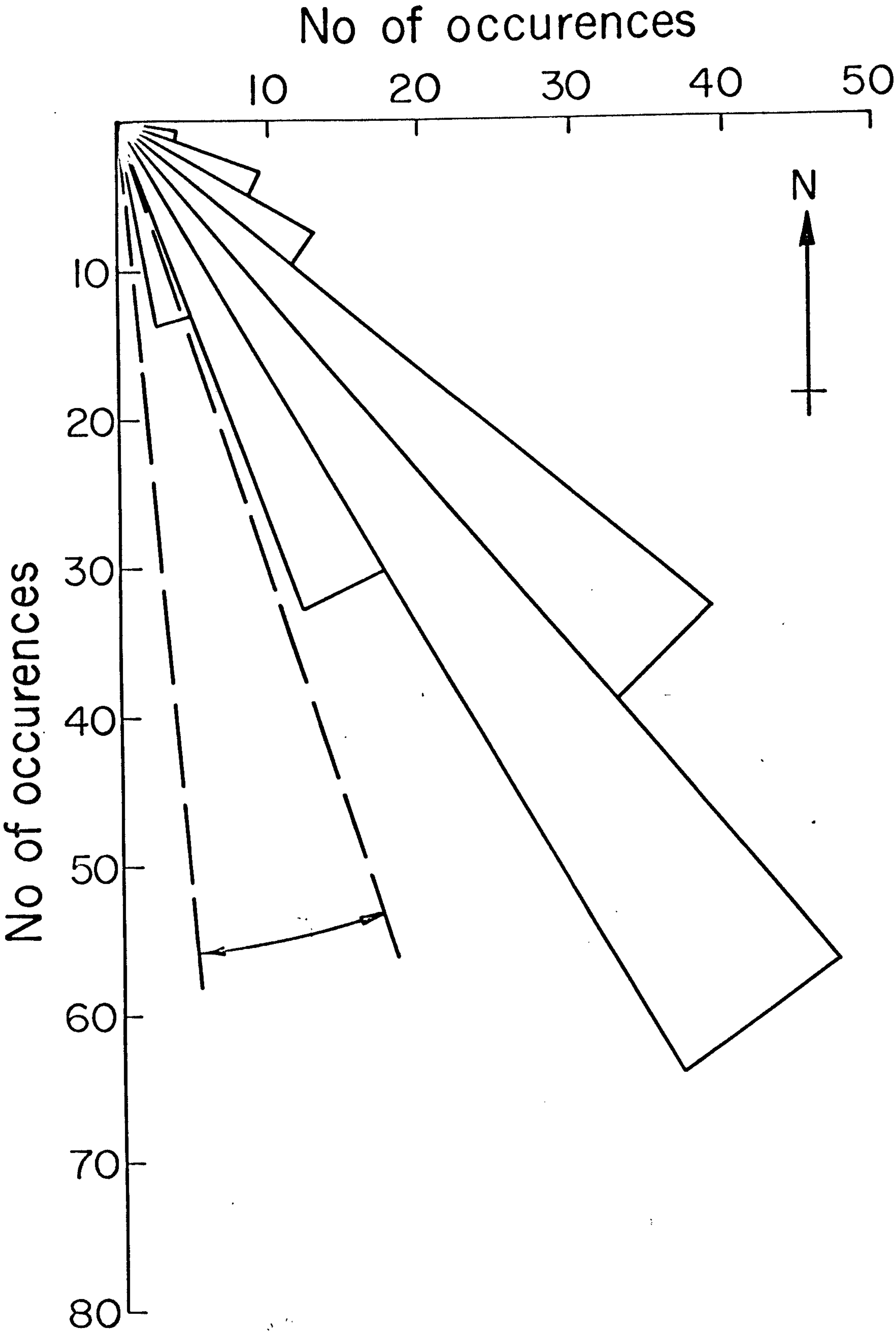


Fig. 16. The diurnal variation of occurrence of magnetic bays at Halley Bay in 1974-75.

Bays are produced by the auroral electrojet and the magnetic field it sets up is analogous to that produced by a current in a long wire. Thus examination of the orientation of the disturbing vectors for each group of bays allows details of the equivalent current systems responsible to be determined. For group A the disturbing vectors are inclined downwards towards the south of the station and would be produced by a westward electrojet to the south of the station. The disturbing vectors of group B would be produced by an eastward electrojet, also to the south of the station. It is notable that the disturbing vectors of groups A and B are each limited to a narrow range of azimuth and elevation. Disturbing vectors in group C however have two distinctly different azimuths; one which occurs in the morning sector and the other in the night-time sector . Those in the night-time sector point south-east, the same as those in group A and likewise are produced by a westward electrojet. The angle of elevation however indicates that in these (few) cases the electrojet is to the north of the station. The disturbing vectors of group C that occur in the evening sector are presumably due to an eastward electrojet. Referring to the theoretical latitude profile (fig 7) of Kisabeth (1972) would suggest that the station is a long way from the electrojet such that the H bays are produced by field-aligned currents. These extreme cases of group c though account for only 1 percent of bays.

For groups A and B the orientation of the disturbing vector is used to define the azimuth from Halley Bay at which the mid-point of the electrojet would be observed. Comparison with the


No of occurences
10
20
30
40
50
N
10
20
30
40
50
60
70
80
No of occurences

This is unexpected since, according to Akasofu (1968), the electrojet flows along the auroral oval where the auroral arcs are situated.

A separate study (Appendix B), made of the azimuths of disturbing vectors and auroral arcs has shown that the results are consistent with induced currents flowing in the sea, adjacent to the station. The intensity of such currents is dependent on the depth of the sea and so near to the coast they are deflected to follow the contours of the sea floor. These induced currents modify the magnetic fields of the electrojet to give the azimuths of the disturbing vector that are observed.

The elevation of the disturbing vectors is closer to horizontal than would be expected for an electrojet located at the site of visual aurora (fig 17). Induced currents in the sea would have the effect of rotating the disturbing vector closer to the vertical so cannot account for this anomaly. Other induced currents may exist deep in the earth but it is not possible to assess their effects on the disturbing vector. These induced currents may be responsible for the apparent difference between the elevation of auroral arcs and the electrojet. Alternatively this difference may arise because the electrojet does in fact lie equatorward of visual aurora, although this is contrary to the results of earlier studies.

A study of magnetic bay activity was made by MacDowell and Blackie (1961) at Halley Bay during the IGY (1957-58). This covered sunspot maximum, in contrast to the 1974-75 study which is at sunspot minimum. 525 bays were observed in the 20 month period from May 1957 to December 1958, compared with 297 bays from January 1974 to December 1975. Comparison of chart records from the two periods show that the same phenomena are being classed as bays and this is confirmed by the breakdown of results shown in table 4. Types A and B correspond to the same class of bays as in the 1974-75 results and occur at the same local times. For types A and B the bays in D were usually positive and negative respectively at sunspot maximum, consistent with the findings at sunspot minimum. However as no magnitudes were given for the bays it was not possible to compare the disturbing vectors from the two periods.

Disturbing vectors for international disturbed days during 1957-58 were plotted by MacDowell and Blackie and interpreted in terms of a line current in the ionosphere, to the south of the station. The magnitude of the disturbing vector, throughout the day, and the elevation and azimuth from Halley Bay of the centre of a line current are shown in fig 18. These elevation and azimuth angles are typically 15^{o} greater than the angles of elevation and azimuth of an equivalent line current shown in fig 17. On the IGY disturbed days the occurrence of a ring current could possibly increase the apparent angles of elevation and azimuth of a westward electrojet. However, with an eastward electrojet the effect of a ring currentwould be to decrease the apparent angles of elevation and azimuth.

Group	Sign of Disturbance			Percent of Total
	H	Z	D	
a)	-	+	+	54.4
	-	+	-	15.8
b)	+	-	+	0.6
	+	-	-	13.6
c)	-	-	+	1.9
	-	-	-	6.4
d)	+	+	+	3.8
	+	+	-	3.5

Table 4. Frequency of Bay-like phenomena in 1957-58, classified according to the sign of the H and Z disturbances. A total of 525 phenomena recorded between May 1957 and December 1958 are classified.

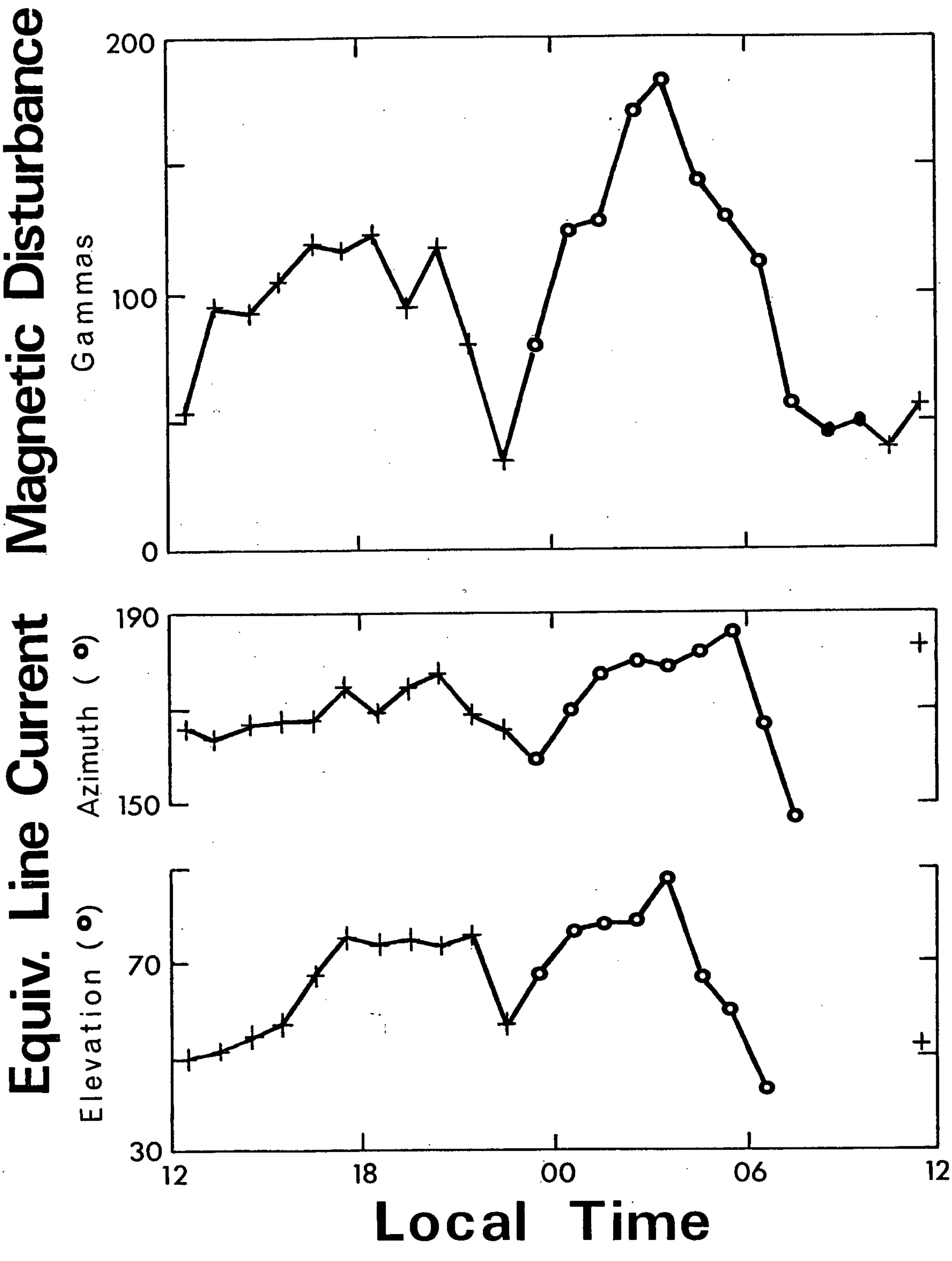


Fig. 18. Magnetic disturbance on international disturbed days in winter 1957 and 1958 represented as line currents (after MacDowell and Blackie, 1961)
a) magnitude of total vector change from disturbed days daily mean
b) azimuth from Halley Bay of centre of line current
c) elevation from Halley Bay of centre of line current

4.2. Pi2 Pulsation Results

Hamilton (1979) tabulated pulsations recorded at Halley Bay using a Rubidium Vapour Magnetometer, in 1975 and 1976. The normal definition of Pi2 was relaxed so that irregular pulsations with periods (from 45 seconds) up to 240 seconds have been accepted as Pi2. The period of the Pi2 pulsations was found to be dependent on the time of occurrence and on the level of magnetic activity. The period of Pi2 steadily decreases from evening, through midnight, to morning; and for any particular local time is found to decrease linearly with the K index of magnetic activity. This is presented in table 5.

Pi2 pulsations occur at night with a distribution roughly centred around local midnight. Analysis of the polarization characteristics of Pi2 showed that clockwise rotation of the Pi2 disturbing vector in the horizontal plane occured predominantly before local midnight while counterclockwise rotation occurs after local midnight (fig 19). The times of occurrence of clockwise and counterclockwise Pi2 are very similar to the times of occurrence of positive and negative H bays respectively.

	20.15	21.45	23.15	00.45	02.15	03.45	05.15	06.45
0	215	175	150	135	126	120	119	118
1	180	155	134	118	108	103	100	98
2	163	137	116	101	93	85	81	78
3	145	120	100	85	74	67	63	59
4	128	103	83	68	58	51	45	40
5	105	85	67	53	43			

Table 5. Typical values of the period (in seconds) of Pi2 for various values of the index of magnetic activity (K) in different 90 minute intervals centred around the local times shown. Local time = UT - 2 hours. K is the sum of the three values of Kp in the interval 18.00 - 03.00 UT.

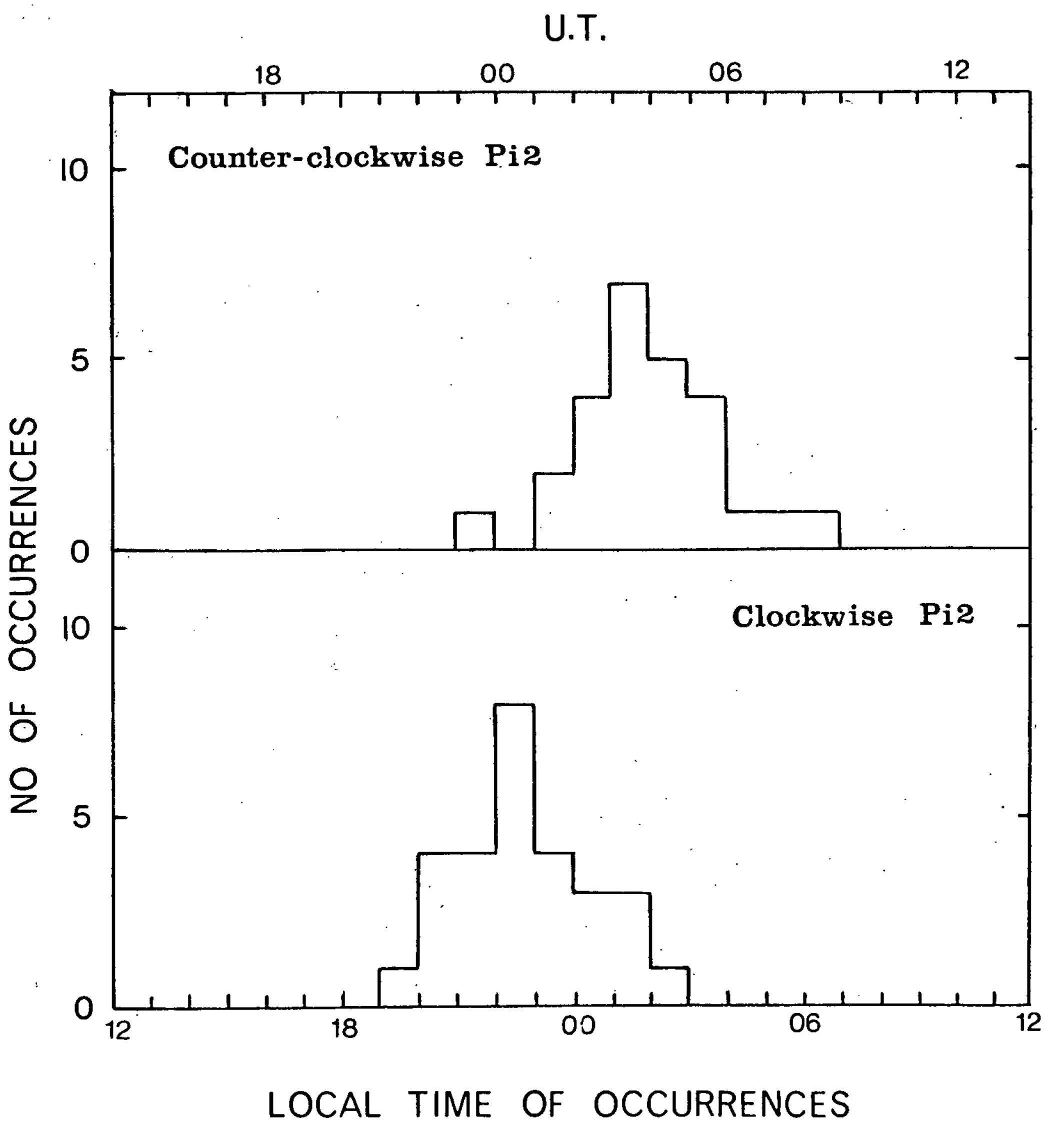


fig. 19. The diurnal variation of occurrence of Pi2 pulsations at Halley Bay in 1976.

Plots of the azimuth of the polarization ellipse, from the data presented by Hamilton, in figs 20a and 20b showed a distribution with a mean NW orientation for counter-clockwise rotating Pi2, but an even distribution in azimuth for clockwise rotating Pi2. The NW orientation is the same as that of the disturbing vectors of magnetic bays and would indicate that these Pi2 are related to the auroral electrojet and are modified by the presence of induced currents in the sea.

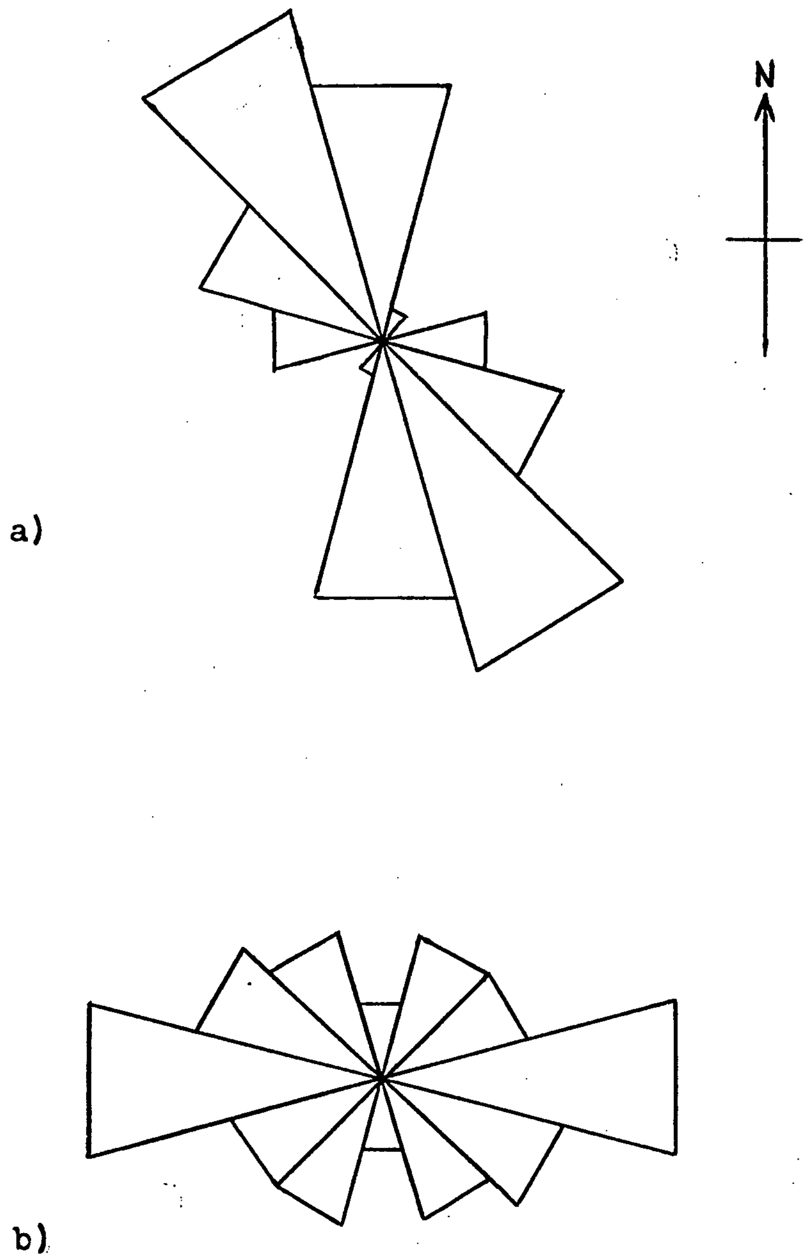


Fig. 20. Distribution in azimuth of polarization of Pi2 pulsations observed at Halley Bay in 1976
a) pulsations with counterclockwise rotation
b) pulsations with clockwise rotation

Whether the different azimuth distributions for counter-clockwise and clockwise rotating Pi2 is significant cannot be determined from the present small amount of data, but this point is certainly worth further investigation.

The polarization characteristics of Pi2 at Halley Bay and its conjugate point, St. Anthony, have been examined by Green and Hamilton (1978). Spectral analysis was used to determine the ellipticity (ε) and azimuth (α) measured clockwise from the meridian, of the horizontal polarization ellipse of Pi2 events recorded simultaneously at the two stations. A positive ellipticity represents counter-clockwise rotation looking downwards in the northern hemisphere. For the same sense of rotation around the field line, ellipticities at conjugate stations would be expected to be equal in magnitude and opposite in sign. A plot of the ellipticities at Halley Bay against those at St. Anthony showed that this is approximately true. A similar plot of the azimuths showed that the angles at Halley Bay are equal but opposite in sign to those at St. Anthony as the conjugate relationship would require. A simple conjugate relationship generally seems to exist between Pi2 at the two stations with the mean phase differences being 10 degrees for H and 170 degrees for D. However towards the end of the year this relationship becomes confused and Green and Hamilton (1978) have attributed this to the presence of a night-time E layer at Halley Bay (due to the 24 hour solar illumination that occurs in the austral summer) which affects the propagation of the pulsations to the ground. This is another feature requiring further examination.

4.3. Correlation With Other Phenomena

A study was made of radio aurora (Shipstone, 1972) at Halley Bay during IQSY, a comparable epoch of the sunspot cycle to 1974-75. Echoes from radio aurora were received from south of the station, typically at a range of 300km (approx 2.7 degrees in latitude) which is, on average, one degree equatorward of visual aurora. Observations, by Shipstone, of movement of the echoing region (fig 21), showed a change from westerly velocities in the evening (before 01.00 U.T.) to easterly velocities in the morning. According to Shipstone the velocities involved (200-400m/sec) are too great to be produced by mass motions and he interpreted them as consistent with the drift velocities of electrons in the electrojet current system. The times of eastward-moving radio aurora agree with the times of occurrence of westward electrojets as determined from magnetic bay results; and there is a similar agreement between the times of occurrence of westward-moving radio aurora and eastward electrojets. This indicates that the electrojet is comprised of a flow of electrons.

It is believed that polar substorms are related to the acceleration of particles in the magnetospheric tail towards the earth. Lezniak and Winkler (1970) found that particle injection from the tail occurred between 22.00 and 06.00 local time, which is consistent with the time of occurrence of negative H bays at Halley Bay. The injected particles are guided into both the north and south auroral zones and so substorm effects should be observed simultaneously in both hemispheres.

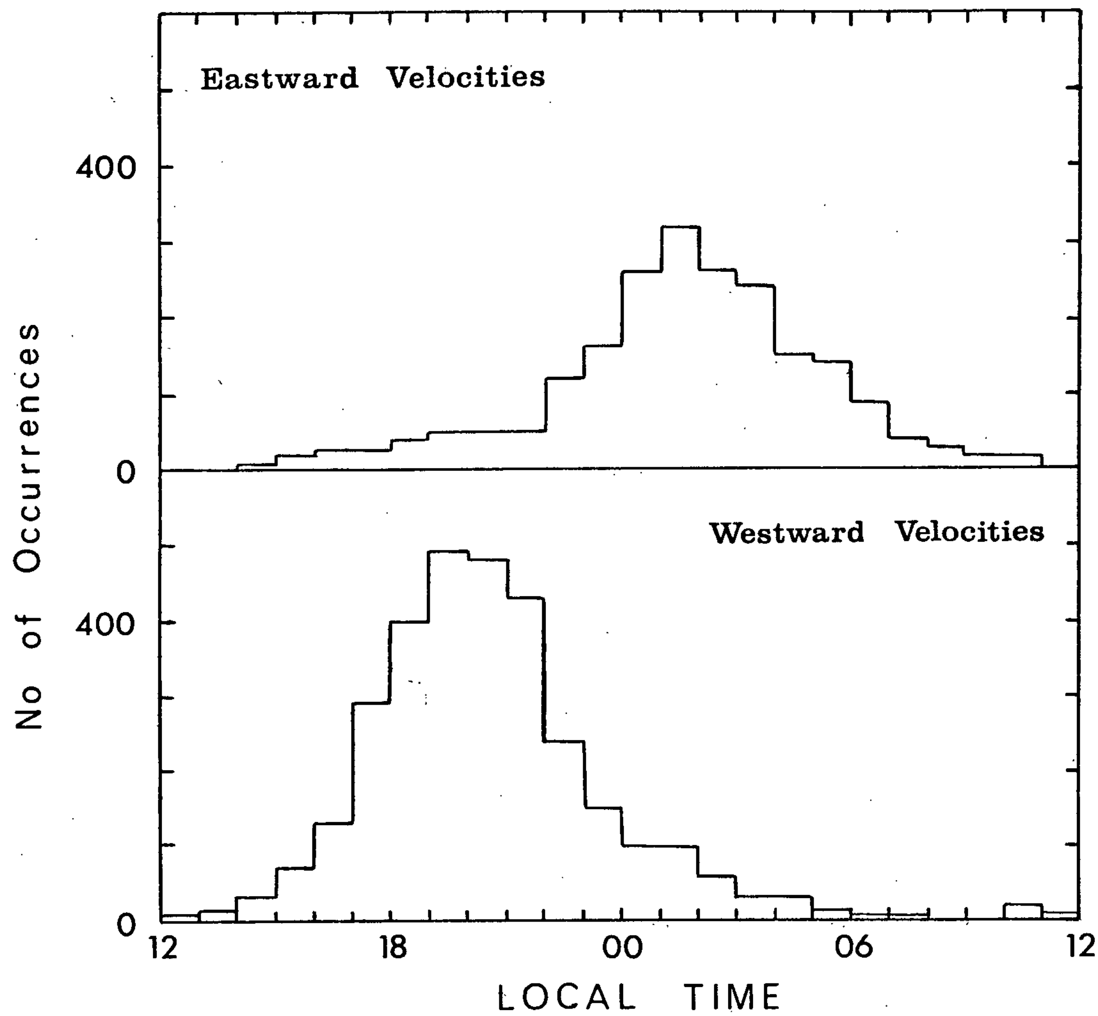


Fig. 21. Diurnal variations in the number of radio aurora with eastward and westward velocities (Shipstone, 1972)

This is shown to occur by the correlation between enhanced absorption, at a northern and southern station, and magnetic bays at Halley Bay (fig 22). Also the correlation of these features with increased electron counts in the tail, observed by satellite, is consistent with the theory of particle injection from the tail during substorms. The link with absorption is illustrated further in the next section.

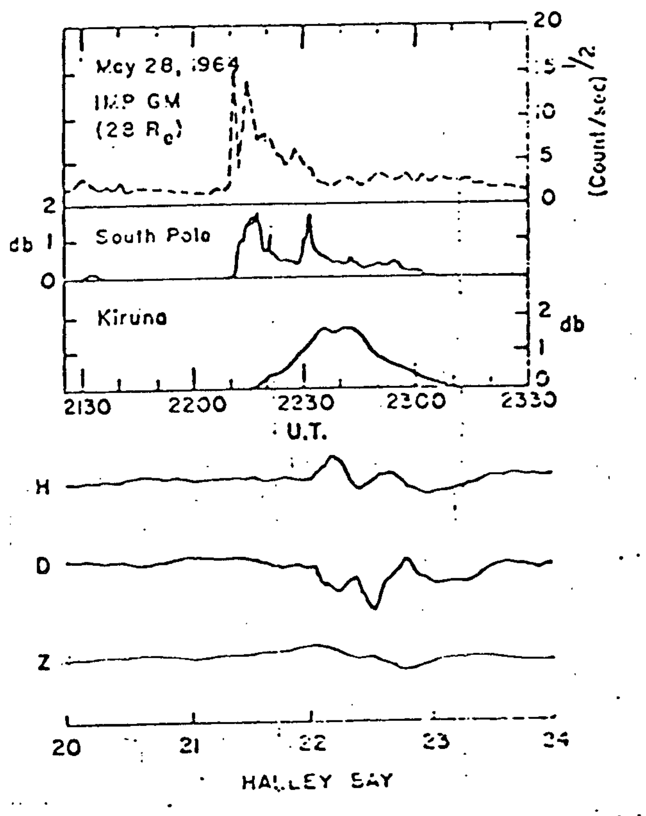


Fig. 22. Electron bursts in the tail region together with increased absorption, detected by riometer, in the north and south auroral zones, during the occurrence of a magnetic substorm at Halley Bay (after Akascfu, 1968).

5. ABSORPTION RESULTS FROM HALLEY BAY

This section presents a study of absorption at Halley Bay during 1974-75, made by the author using riometer and ionosonde measurements. Comparisons are made with the ionosonde and A1 measurements made at Halley Bay during the IGY (1957-58) by Bellchambers et al (1962). Also, details of VLF emissions at Halley Bay are presented from a statistical study of whistler and VLF activity during 1972 made by Thomas (1975).

The riometer used at Halley Bay is a commercially produced model from the design by Little and Leinback (1959) and operates on 27.6MHz. The riometer records the signal intensity of cosmic noise received; and the antenna is directed at the south celestial pole to minimise the siderial variation in the received signal. In practice, however, this cannot be entirely eliminated and it is necessary to determine a quiet-day curve representing the unabsorbed signal level. Any drop in signal level below this curve then gives a measure of the absorption suffered by the cosmic noise in passing through the ionosphere. In the results presented here short period absorption occurrences were identified, by inspection, from the original cosmic noise record. However, to identify longer periods of enhanced absorption, I used an hourly sampling of absorption values, obtained after removing the quiet-day curve. An absorption event was then defined as the occurrence of absorption greater than 1dB for one or more consecutive hourly values.

An ionosonde makes radio soundings of the ionosphere and receives both ordinary (o) and extraordinary (x) reflections from the E and F layers. The characteristic frequency of a layer is designated by "f, mode, layer name": thus the characteristic frequencies for the F2 layer are foF2 and fxF2. The top frequency at which echoes are received from the F layer is labelled fxI. When there is no spread F present fxI = fxF2, but commonly there is spread F and as a result fxI is greater than fxF2.

The condition when no echoes are received is known as "blackout". This occurs when the absorption at the highest echo frequency, normally fxI, exceeds the threshold level of the ionosonde. The occurrence of blackout on ionosondes has been used as an indication of abnormal absorption. However evidence is presented in Appendix A to show that the occurrence of blackout is seriously affected by changes in fxI values. This makes blackout occurrence an unreliable indicator of enhanced absorption.)p the A1 technique involves making radio soundings of the ionosphere on certain fixed frequencies. The frequencies are chosen so that the signals are reflected by the E region. These signals will be parially absorbed in the D region and so variations in the received signal strength give a measure of the absorption suffered by the signal in the D region.

5.1. Rapidly Varying Absorption

For the majority of magnetic bays recorded in 1974 and 1976 the riometer operated at Halley Bay showed an increase in D region absorption which commenced at the same time as the bay. In many cases the magnetic and riometer variations appeared nearly identical. For seventy five percent of bays there was also blackout on the ionosonde but this often persisted beyond the duration of the bay. Blackout results from a variety of causes and occurs far more frequently than magnetic bays so it would appear unlikely that it is directly related to substorms. However cases have been identified where the occurrence of blackout is limited to the duration of a specific bay (fig 23).

Thus absorption occurs simultaneously with magnetic bays but the position and extent of the affected zone are difficult to assess. The ionosphere makes vertical soundings of the ionosphere but also frequently receives echoes obliquely. Thus for blackout to occur there must be enhanced D region ionization vertically above the station and often over a wider area as well. The electrojet occurs poleward of the station and, from the orientation of the disturbing vector, was estimated to lie at an angle of elevation between 40 degrees and 70 degrees. The riometer uses a directional aerial (3dB bandwidth of 15 degrees) pointing due south at an elevation of 75 degrees so views an area of the ionosphere equatorward of the electrojet. Thus although the poleward extent of the absorption region cannot be assessed, the results indicate that the absorption region does extend equatorward of the electrojet.

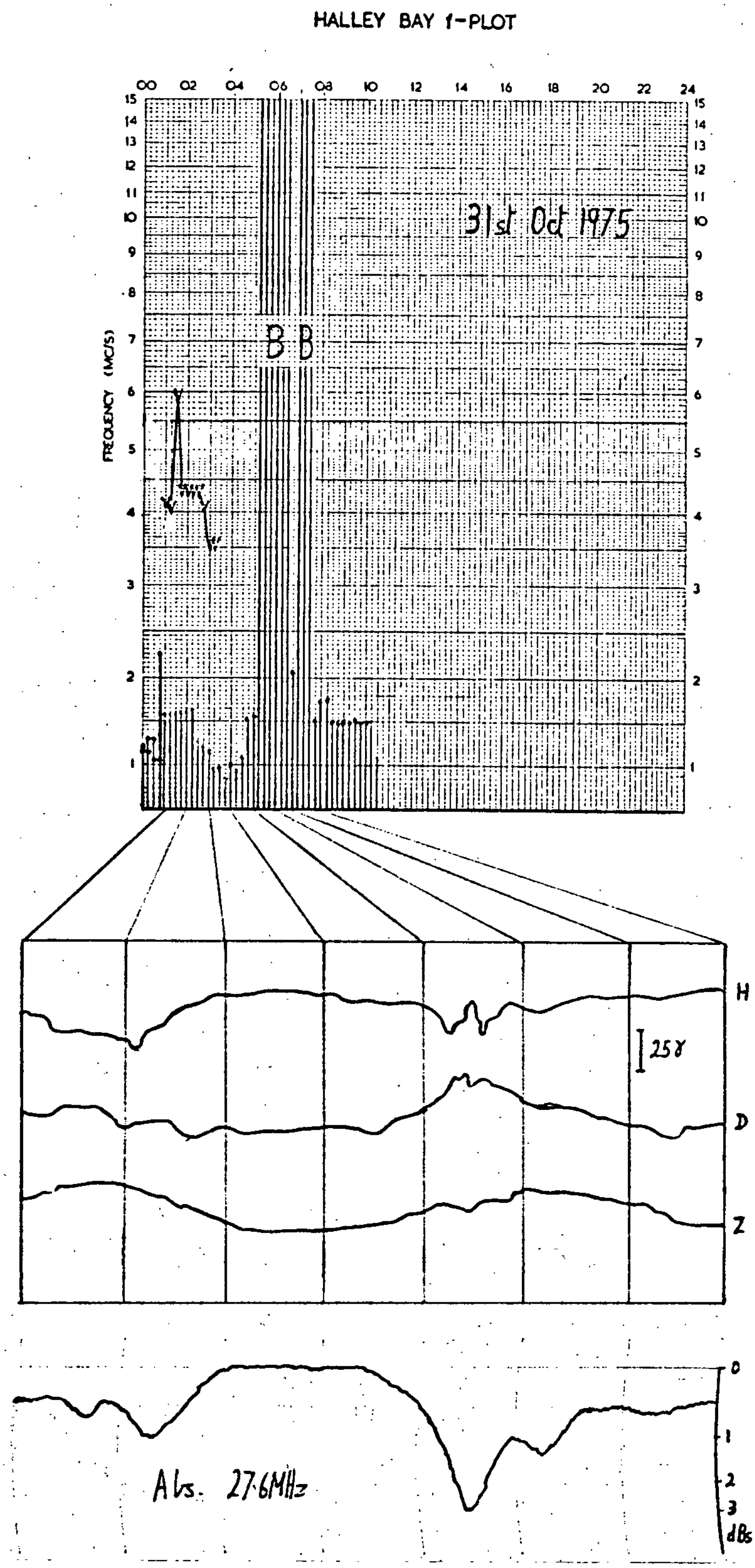


Fig. 23. Magnetic and riometer records and an f-plot of ionosonde measurements for two magnetic bay events:
i) at 01.00 showing above average foEs on the f-plot
ii) at 05.00 showing blackout on the f-plot

5.2. Slowly Varying Absorption

Absorption events were found to occur principally on the dayside. This can be seen from the percentage occurrence at each hour of absorption>1dB and absorption>2dB (fig 24) which shows that the former peaks at 14.00 local time while the latter peaks slightly earlier. The occurrence of blackout at Halley Bay has a maximum, at 06.00 local time, considerably earlier than the maximum occurrence of absorption events.

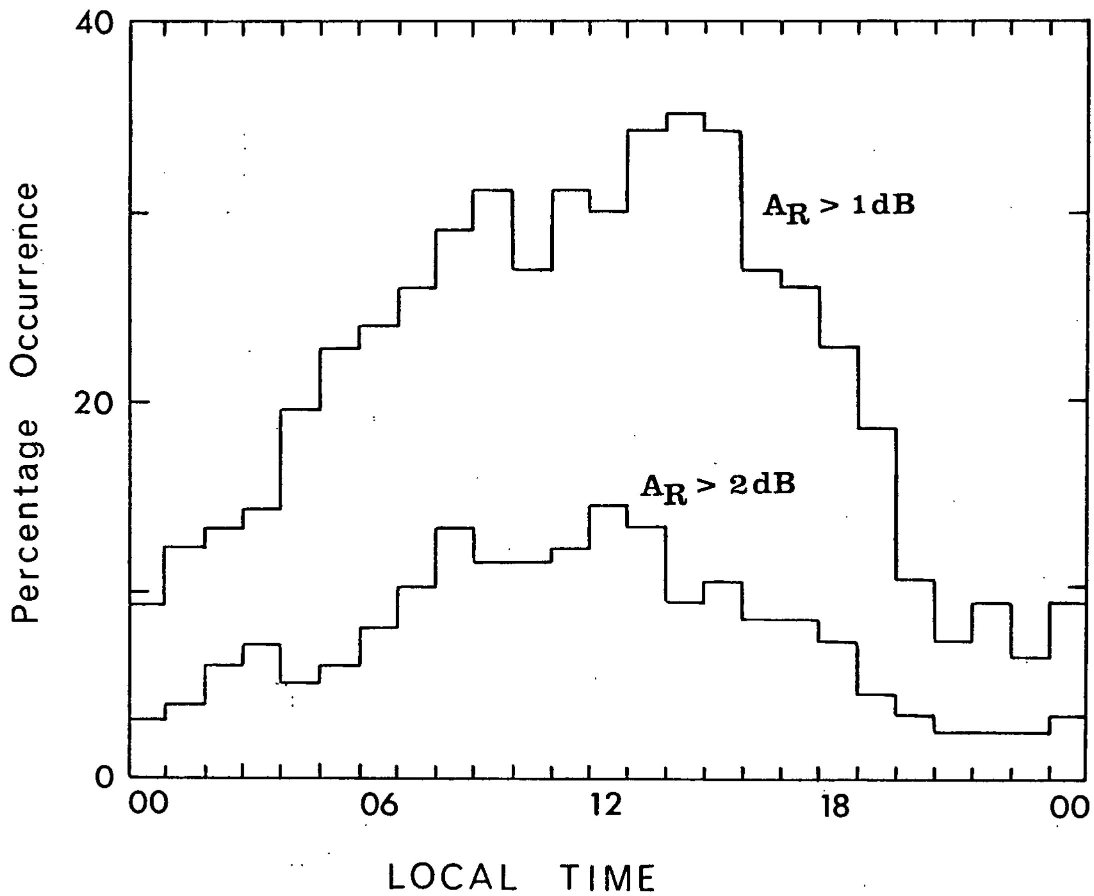


Fig. 24. The percentage of hours in 1974 with absorption > 1dB and > 2dB at Halley Bay.

To examine the seasonal variation of absorption events the diurnal variation of absorption events was first produced for each month in 1974 and 1975. The results for the summer months were then combined to give the mean diurnal variation of absorption events for the summer season; and the same procedure was also used to give the mean diurnal variation of absorption events for the equinoctual and winter seasons. These results (fig 25) show that absorption events are most frequent at the equinoxes and occur least often in winter.

The shape of the diurnal variation is also shown by fig 25 to change with season, with the peak in occurrence earlier in winter than in summer. In order to determine the significance of this, error bars are drawn which show the standard deviation of the mean. Even allowing for the deviations shown, it would appear that the diurnal variation in summer peaks at 13.00 - 18.00 local time while the diurnal variation in winter, although not so pronounced, peaks between 09.00 and 12.00 local time. The data suggest that the peak of the diurnal variation becomes progressivly earlier as the seasons change through summer and equinox to winter.

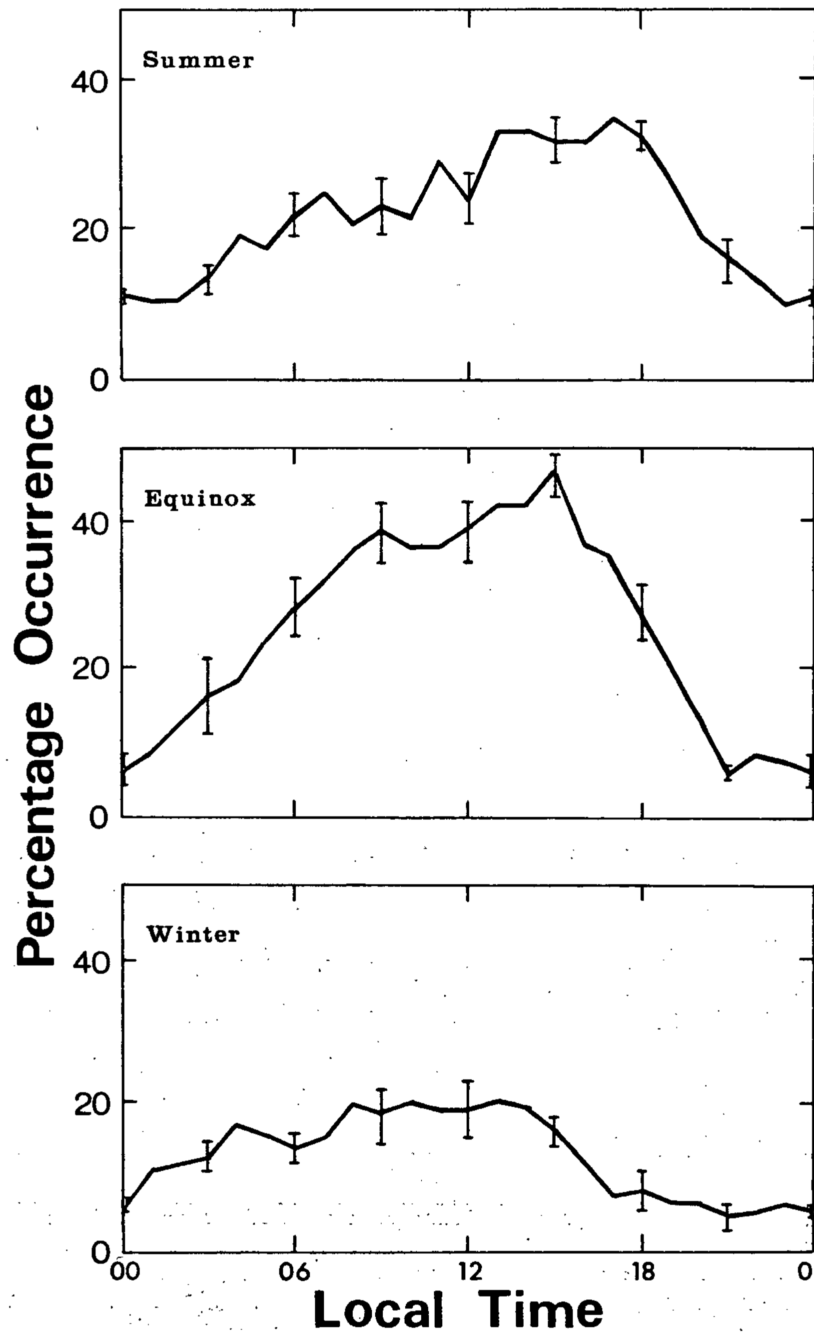


fig. 25. The mean monthly percentage occurrence of absorption events in 1974-75 for
a) Summer: Nov, Dec, Jan, Feb
b) Equinox: Mar, Apr, Sep, Oct
c) Winter: May, Jun, Jul, Aug
Therefore each curve is the mean of 8 months' data and the error bars show the standard deviation.

5.3. Comparison With IGY Results

During the IGY, measurements were made at Halley Bay of the absorption at 2.2MHz and 4.0MHz using the A1 technique, as well as the recordings of fmin values and the occurrence of blackout. Fmin was found to be closely related to solar zenith angle but was also affected by the level of magnetic activity (Bellchambers et al, 1962). The occurrence of blackout during IGY shows the same diurnal variation as in 1974-75. The maximum blackout occurrence in IGY is only 15 percent compared with 30 percent in 1974-75, but during IGY fxI was consistently twice the corresponding values in 1974-75. Blackout occurrence has been shown to be dependent on fxI values (Appendix A) so these results do not indicate any significant differences in the occurrence of enhanced absorption in the two periods.

Comparison can be made between the A1 measurements on 2.2MHz and 4.0MHz during the IGY and the riometer measurements on 27.6MHz in 1974-75 by presenting the data in terms of an absorption index, A, given by

$$A = L \cdot (f + f_L)$$

Where L = absorption observed at frequency f

and f_L = electron gyro frequency.

Fig 26 shows the monthly median values of A for 1957, 58, 74, and 75 and the mean seasonal curves for the two periods. It can be seen that these seasonal variations are remarkably similar, the only difference being that the general level of absorption appears to be higher in 1974-75. However this may only be due to an increase in the number of absorption events. It should be noted that an absorption event of 1dB on the riometer corresponds to an absorption index of about 800dB, so the occurrence of only a few more absorption events would significantly increase the mean absorption index. Thus the data does not indicate any major change in the level of absorption or the number of absorption events between 1974-75, sunspot minimum, and 1957-58, sunspot maximum.

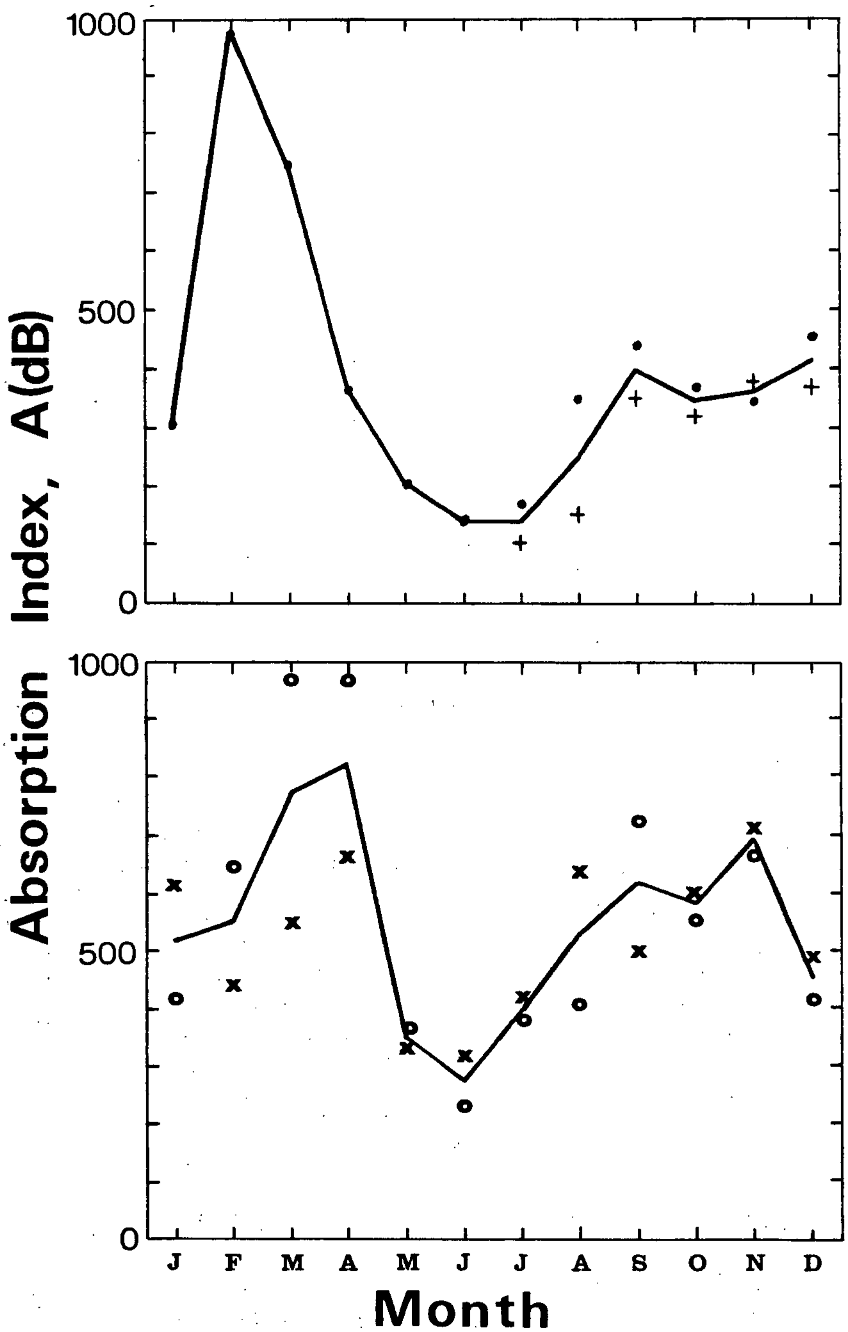


fig. 26. The seasonal variation of the absorption index at noon
a) calculated from monthly medians of A1 measurements
b) calculated from monthly medians of riometer measurements.

5.4. Correlation With VLF Emissions

This section is concerned with VLF emissions because of their possible association with electron cyclotron instability and the precipitation responsible for dayside absorption. Synoptic VLF recordings have been made at Halley Bay for Dartmouth College, USA, since 1971 and a statistical study of the whistlers and VLF emissions so recorded during 1972 has been made by Thomas (1975).

Thomas distinguished between hiss and discrete emissions, in his study of VLF emission activity, and found that both occur predominantly during the day. The recordings were split into two frequency ranges; a low range from 100Hz to 1.5KHz and a high range from 1.5KHz to 10KHz. The majority of hiss occurred in the low frequency range whereas discrete emissions were found in both the low and high frequency ranges.

Both VLF emissions and absorption events are dayside phenomena with a maximum occurrence in the middle of the day, but there is no close similarity between the shapes of the diurnal variation of the two phenomena. At the time of maximum activity 60 percent of the recordings contained hiss and 40 percent had discrete emissions compared with absorption events which have a maximum occurrence of less than 30 percent. However no information is given about the number of emissions per recording of about their intensity so the comparison with absorption may be misleading. Hence a closer examination of the recordings is required to determine whether or not there is any direct correlation between absorption and VLF emissions

6. DISCUSSION

This chapter presents the authors contributions to the theory of substorms.

First, the local time distribution of substorm phenomena observed at Halley Bay is examined and this information is used to derive a new unified picture of substorm phenomena and their effects on the ground.

Most of the Halley Bay results conform to the picture of substorm processes presented in chapters 2 and 3. However in order to provide a complete explanation of the observed phenomena there are two substorm features that require further investigation. The first is the occurrence of an eastward electrojet; and in section 6.2 a model is developed to account for this feature. The other problem is the uncertain role of photodetachment with regard to auroral absorption and in section 6.3 the unique location of Halley Bay is used to clarify the situation.

6.1. Local Time Disturbance Pattern

6.1.1. Magnetic Disturbances

Throughout the data analysis it was clear that phenomena had different characteristics in the evening sector compared to in the midnight morning sector. This is especially obvious in the magnetic bay data where a change from positive H bays to negative H bays occurs at 22.00 local time. This feature of magnetic bays was first noted by Harang (1946) and it is now recognised that many features change at the "Harang Discontinuity". The fundamental feature of the discontinuity is now identified as a change from a poleward to an equatorward electric field across the auroral zone (fig 27). Radio aurora at Halley Bay also showed a change at the Harang discontinuity which is associated with the different electrojets responsible for the change in the magnetic bays. The distribution of Pi2 overlapped that for both positive and negative H bays however the polarisation changed from clockwise before 00.00 local time to counterclockwise afterwards. Whether this change is associated with the Harang discontinuity is uncertain. However the Harang discontinuity is located at different local times in different latitudes so the "later" Pi2 time might indicate that the Pi2 source region is at lower latitudes than the electrojet responsible for magnetic bays.

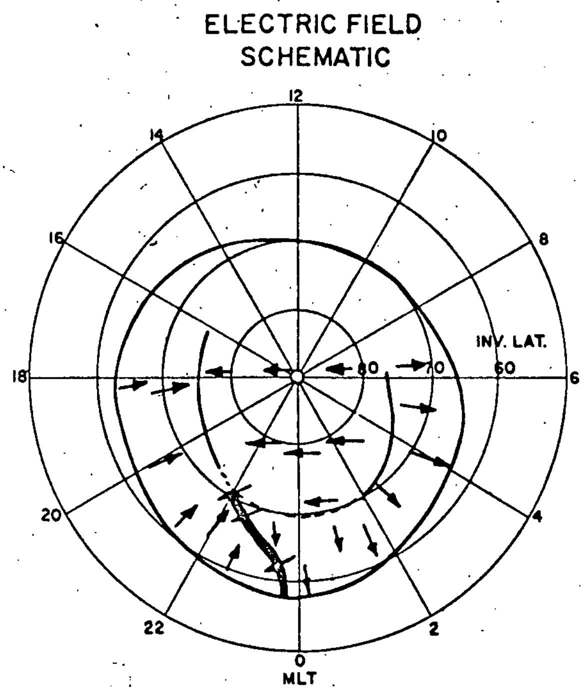


fig. 27. Electric fields in the polar cap and the position of the Harang discontinuity where the electric field across the auroral zone changes from equatorward to poleward. (Maynard, 1974).

6.1.2. Ionosperic Disturbances

The absorption results show a discontinuity at 04.00 local time analagous to the Harang discontinuity in the magnetic results. Before 04.00 the absorption is rapidly varying and of short duration while after 04.00 longer periods of slowly-varying absorption occur. This effect is evident in the distribution of substorm phenomena reported by Hartz and Brice (1967). They classify rapidly varying auroral absorption, together with discrete aurora and auroral Es, as "discrete" events; and they label slowly varying absorption, along with diffuse aurora, as "diffuse" events. The discrete events are produced by impulsive bursts of "splash" precipitation, and occur along the auroral oval, with peak occurrence just before local geomagnetic midnight. In contrast, diffuse events are associated with slowly varying "drizzle" precipitation with a maximum at 09.00 mean geomagnetic time. Fig 28 shows the distribution of events for the Northern hemisphere.

As explained in section 3, the splash precipitation is caused by direct injection of particles from the tail, while the drizzle precipitation comes from electrons trapped in the radiation belt drifting round into the morning sector. The diurnal variation of absorption at Halley Bay can basically be explained by this precipitation pattern.

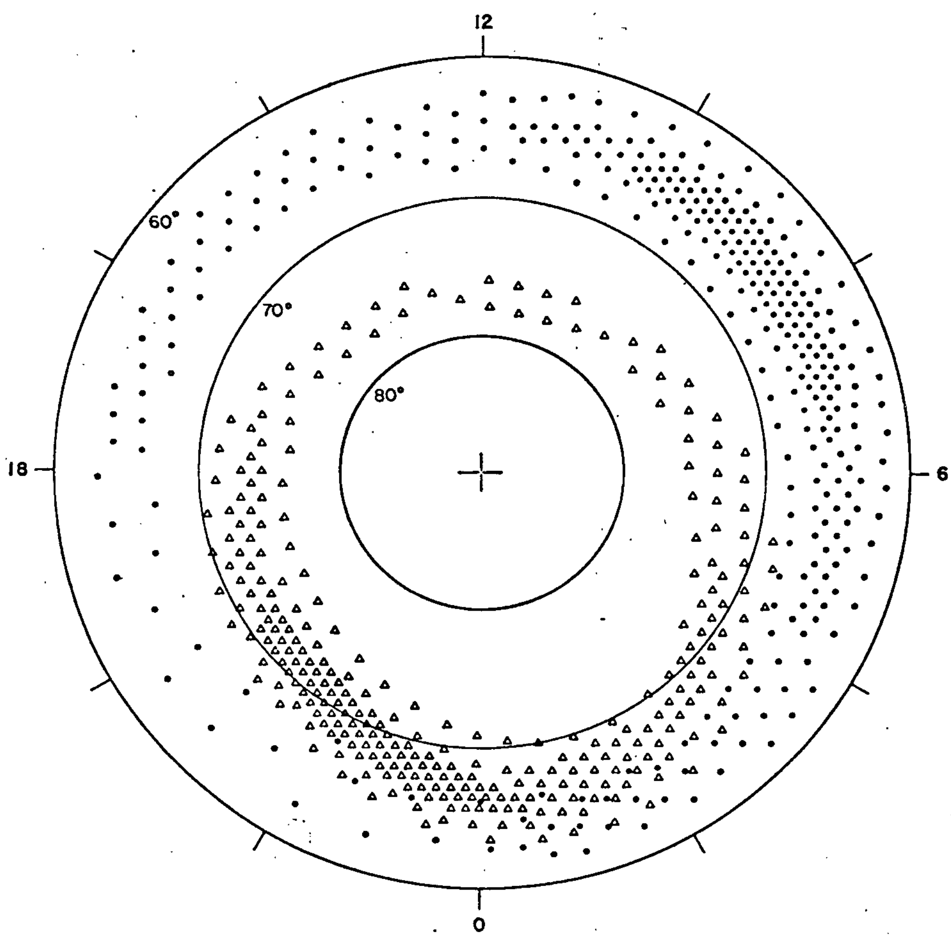


Fig. 28. Idealized representation of the distribution of 'diffuse' events (dots) and 'discrete' events (triangles) after Hartz and Brice (1967). An auroral zone station will see a change from discrete events to diffuse events at about 04.00 local time.

6.1.3. Overall Picture Of Substorm Effects

To summarise: the principle polar substorm processes can be pictured (fig 29) as particle injection on the nightside direct into the ionosphere, together with penetration of higher energy particles across field-lines to become trapped in the outer radiation belt. Once in the radiation belt the protons drift west into the evening sector and ion cyclotron turbulence causes their precipitation. The electrons, conversely, drift east into the morning sector and precipitate into the ionosphere as a result of pitch angle diffusion or electron cyclotron turbulence.

The disturbance pattern seen on the ground as a result of the above precipitation pattern is shown schematically in fig 30. It must be emphasised that this disturbance pattern is fixed in space and that the earth rotates underneath it. Thus an auroral zone station, such as Halley Bay will observe a specific type of disturbance depending on where it is when a substorm occurs. To illustrate this, suppose substorms occur at 22.00, 04.00 and 10.00 U.T. Local time at Halley Bay is U.T. - 2hrs and so the resulting magnetic and absorption records would appear as shown in fig 31. A local-time disturbance pattern can be used to provide several hours warning of disturbances.

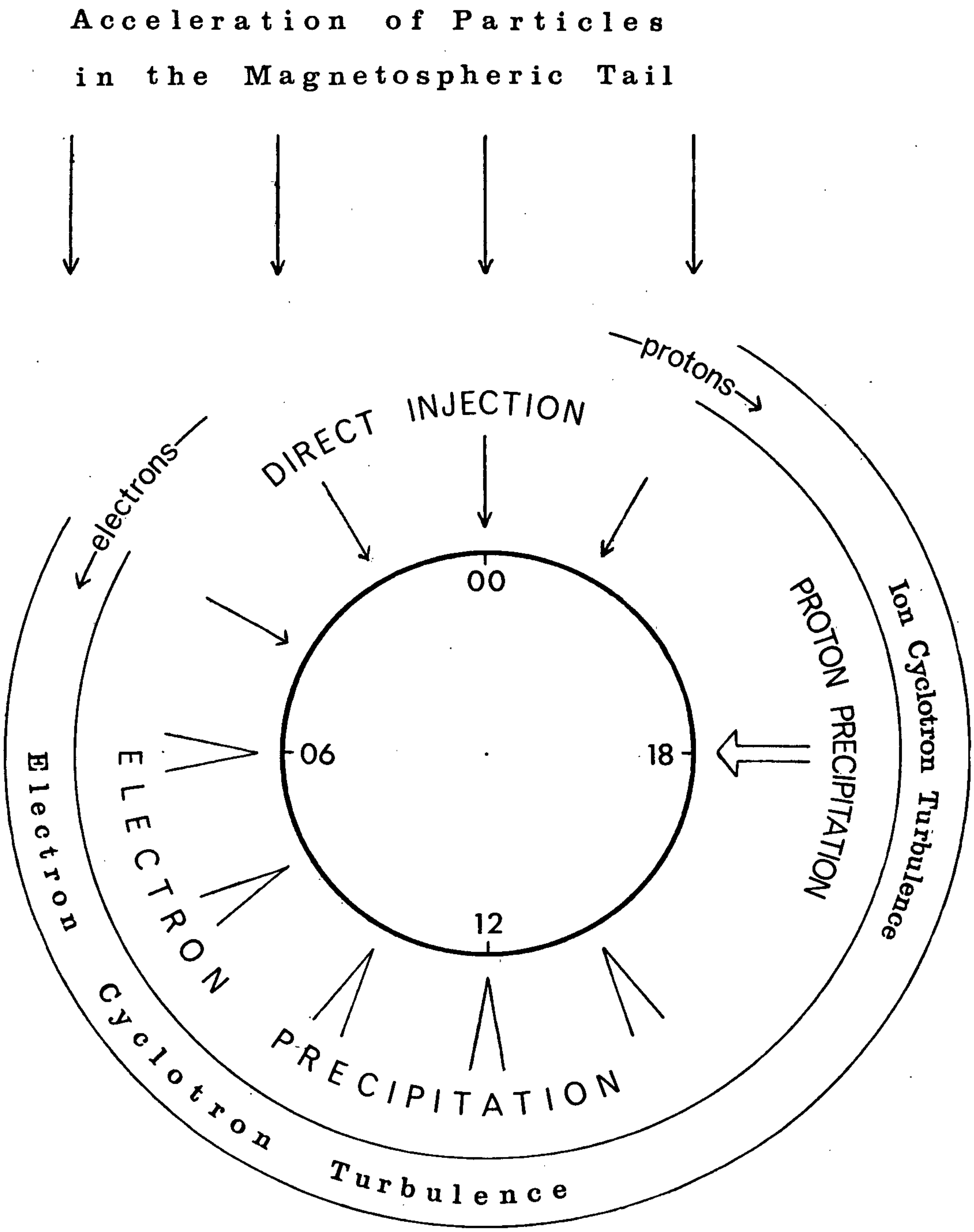


Fig. 29. Schematic illustration of the polar substorm precipitation.

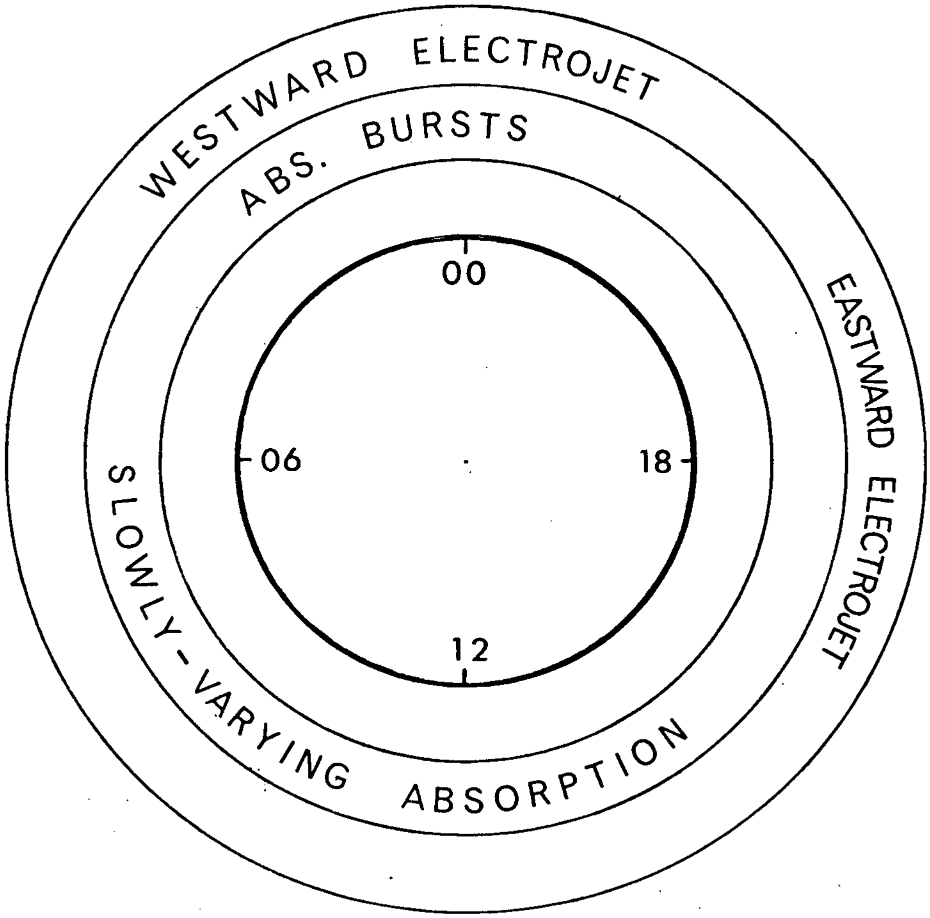


Fig. 30. Schematic illustration of the effects in the ionosphere of the precipitation pattern of Fig 29.

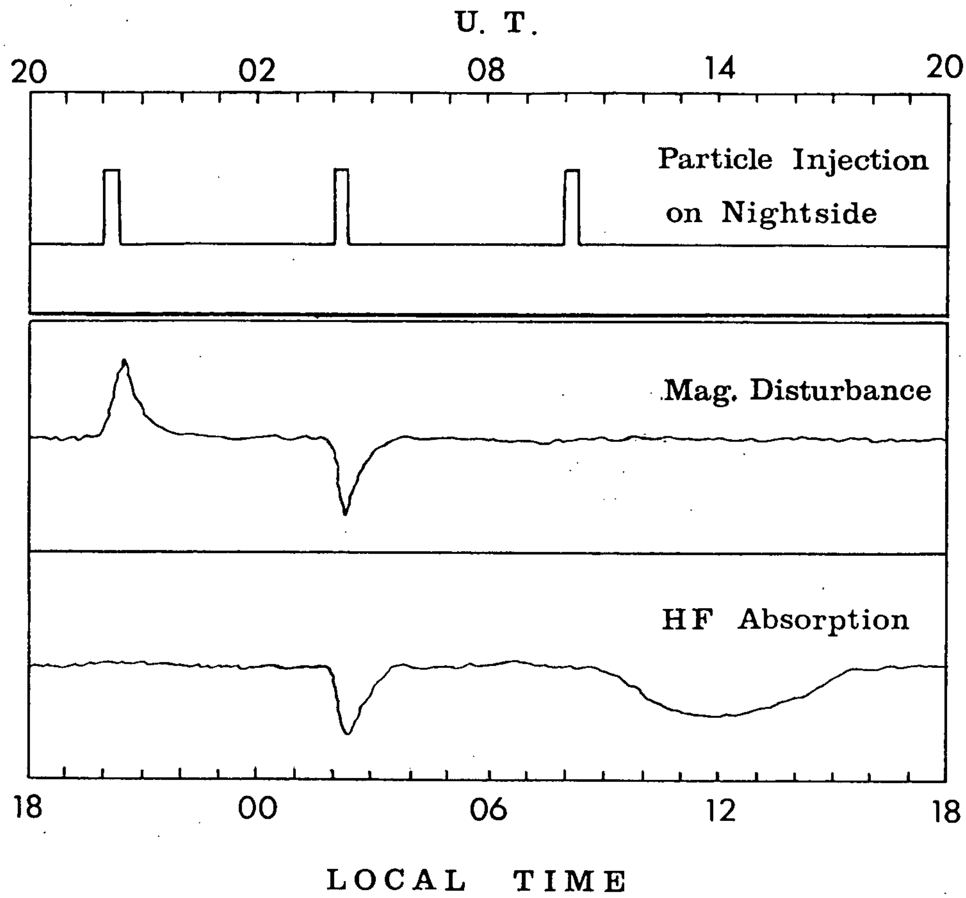


fig. 31. Schematic illustration of the different disturbances, depending on local time, produced at a ground observatory by a burst of particle injection on the nightside of the earth.

The nightside events are dominated by the effects of particle precipitation. However the dayside absorption is affected by the solar illumination of the ionosphere and so evidences a seasonal variation (see fig 25 and section 6.3). The number of disturbances also shows a seasonal variation with a peak in the equinoxes.

6.2. The Cause Of The Eastward Electrojet

The eastward electrojet cannot be simply explained like the westward electrojet. The low occurrence of positive bays compared to negative bays at Halley Bay suggests that substorm injection of particles alone is not sufficient to give rise to an eastward electrojet. It is therefore worthwhile to examine the relationship between the eastward electrojet and two other evening features: the partial ring current, and the plasmasphere bulge.

6.2.1. Association With The Partial Ring Current

There is considerable evidence that a partial ring current occurs at the same time as the eastward electrojet. For instance Kamide and Kukushima (1972) investigated the latitude profile of magnetic disturbance in the evening sector and found that the H decrease at middle and low latitudes is much greater than that expected from the return current of an eastward electrojet. Satellite observations nave also detected a partial ring current and Frank (1970) found that the current is carried by low energy protons. These prctons would be injected from the tail during a substorm, become trapped on closed field lines, and drift westward under the influence of the magnetic field. However the intensity of the partial ring current shows little relationship with substorm magnitude, and instead is well correlated with the previous integrated southward IMF (Clauer and McPherron, 1978). Clauer and McPherron also report a strong correlation between the partial ring current magnitude and the AU index which supports the hypothesis that closure of the partial ring current occurs through the eastward electrojet. This is consistent with the substorm current system proposed by Kamide and Fukushima (1972) which is shown in fig 32.

The Halley Bay positive H bays (fig 18) suggest that the eastward electrojet (and partial ring current) should be centred at 18.00 local time rather than as shown. The occurrence pattern of positive H bays may be misleading because an eastward electrojet extending further into the nightside may not produce positive H bays at these later local times because of the occurrence of an overlapping westward electrojet. However the time of occurrence of positive H bays has not yet been satisfactorily accounted for by any of the theories proposed (Nishida, private communication, 1979).

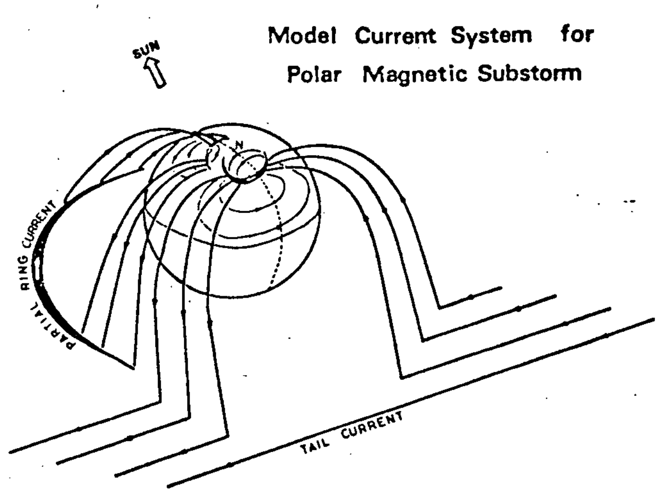


Fig. 32. Schematic illustration of a model current system for a typical polar magnetic substorm, showing the occurrence of a partial ring current (Kamide and Fukushima, 1972).

6.2.2. Evening Bulge In The Plasmapause

The plasmasphere has a bulge in the evening sector coincident with the location of the eastward electrojet. Whether there is a connection between the two is uncertain however this possibility is certainly worth consideration.

Experimental evidence indicates that the inner boundary of the ring current is closely associated with the plasmapause (Russell and Thorne, 1970); and it has been suggested (eg Thorne, 1972) that this is due to local enhancement of the proton loss rate at the plasmapause. However Bernstein et al (1974) report that precipitation of ring current protons actually occurs over a wide region outside the plasmapause.

A popular theory for proton precipitation involves ion cyclotron instability (eg Thorne, 1972). However Coroniti et al (1972) have suggested that electrostatic ion instability might be more significant. A review of the possible precipitation mechanisms has been made by Ashour-Abdalla and Kennel (1978) and they conclude that electrostatic ion instability appears the most likely process, but that it is critically dependent on the cold electron density and temperature. The cold electron density inside the plasmaphere is markedly different from that outside and the plasmasphere may prove to be a region that inhibits electroststic ion instability. In consequence the evening bulge of the plasmasphere could affect the distribution of proton precipitation and as a result give rise to the eastward electrojet. This possibility will be considered in the next section.

6.2.3. Proposed Mechanism For The Eastward Electrojet

During a substorm there is electron precipitation into the nightside ionosphere. Also enhanced convecton injects protons into the 18.00-24.00 local time sector (Cornwall et al, 1970) and these become trapped in the outer radiation belt. These trapped protons drift westward under the influence of the magnetic field, and so form a partial ring current. Closure of this current system could be achieved by a circuit featuring a flow of electrons up field lines. However for the system proposed here, it is assumed that a significant portion of the downward field-aligned current is carried by precipitating protons.

In drifting round to the afternoon sector some of the protons will pass through the evening bulge of the plasmasphere. It is proposed that the mechanism for proton precipitation is electrostatic ion instability, and that this instability is inhibited inside the plasmsphere. This would result in an uneven distribution in the precipitation of drifting protons. Greater precipitation would occur on the day-side of the plasmasphere bulge, and in a simplified picture, this can be considered as a downward field-aligned current. The electron precipitation on the nightside constitutes an upward field-aligned current. Closure of the current system in the ionosphere by a westward flow of electrons thus produces the eastward electrojet.

6.3. The Role Of Photodetachment In Auroral Absorption

6.3.1. D Region Chemistry

Ionisation of the atmospheric constituents in the D region initially produces free electrons and positive ions. However, in contrast to the higher regions of the ionosphere, there also exist negative ions. Negative ions are principally observed below 80km, however negative ions have also been detected at greater heights (Mitra, 1978). Negative ions are formed by an initial attachment of free electrons to O and O_2 to form O^- and O_2^-. Charge exchange collisions result in the production of a series of ions with increasing electron affinity until stable negative ions such as NO^- and $X^-(H_2O)$ are formed. At intermediate steps the main process of loss of negative ions are through photodetachment by solar radiation or by collisional detachment involving neutral constituents of the atmosphere (Mitra, 1978).

The rate of photodetachment is dependent on the solar zenith angle and so will occur more in summer than in winter giving rise to a seasonal effect. Also, if the major ion is O^-, the wavelength required for photodetachmemt is 2870nm. This is in the visible spectrum so the occurrence of photodetachment would be controlled by sunrise and sunset.

Whether photodetachment is a significant process with respect to auroral absorption depends on whether negative ions occur at the heights where auroral ionisation occurs. At most auroral zone stations the seasonal change in solar radiation is not large enough for this problem to be resolved. However the uniquely high geographic latitude of Halley Bay should make any effect of photodetachment more easy to detect.

6.3.2. Halley Bay Results

At Halley Bay the changes with season in the diurnal variation of absorption events (fig 25) suggest that photodetachment is a significant process. At the equinox, the diurnal variation, roughly centred about noon and with rapid changes in absorption at 06.00 and 18.00 local time, indicates that photodetachment is the controlling process. While in winter the absence of photodetachment should allow the precipitation pattern to be most easily recognised; and, in fact, the maximum occurrence in winter, between 09.00 and 12.00 local time, is consistent with the maximum time of "drizzle" precipitation in fig 28. Further evidence of the competing effects of particle precipitation and photodetachment can be seen in fig 24, which shows that the peak occurrence of the larger absorption events (abs > 2dB) is shifted more towards the peak "drizzle" time than the peak occurrence of the standard absorption events (abs > 1dB). This would indicate that the great precipitation, responsible for abs > 2dB, is overcoming the photodetachment control that affects smaller absorption events.

6.3.3. Production Of Auroral Absorption

Auroral absorption is primarily attributable to the D region ionisaticn produced by electron precipitation. The continual loss of free electrons, by attachment, to form negative ions, however reduces radio wave absorption. This is the situation at Halley Bay in winter where little absorption is observed. However when there is solar illumination of the ionosphere photodetachment of electrons counteracts the loss by attachment and the absorption is correspondingly greater.

The Halley Bay results are not conclusive and so the above outline of auroral absorption is only tentative. However the Halley Bay results are consistent with an ionospheric model in which photodetachnent is significant with regard to auroral absorption.

7. CONCLUSIONS

The wide range of data collected by the author at Halley Bay has been used to examine the validity of present theories regarding many aspects of polar substorms. The division of substorm features by Hartz and Brice (1967) into 'discrete' and 'diffuse' phenomena is judged to be reasonable. However a third class, for evening features, should be added; and a substorm disturbance pattern is developed with this included. This features direct particle precipitation into the nightside ionosphere which causes rapid variations in absorption, as well as the westward electrojet which is responsible for the magnetic disturbances in that sector. Also some particles become trapped in the outer radiation belt: protons drift into the evening sector and give rise to the eastward electrojet, while electrons drift round to the morning and day side where they produce long period variatins in absorption.

Detailed examination of the observations revealed several previously unexplained features. The diurnal and seasonal variations in the occurrence of enhanced absorption, detected by the riometer, indicate that photodetachment of negative ions by sunlight has a significant effect on auroral absorption. Also it has been shown that the occurrence of blackout on the ionosonde is seriously affected by fxI values and so is misleading as an indicator of enhanced absorption: a better indicator being the occurrence of absorption at 27.6MHz.

Theories for polar substorm features in the night and morning hours are reasonably satisfactory. However for evening phenomena the theories are inadaquate. It is proposed (see section 6.3) that the plasmasphere bulge may modify the proton precipitation pattern in the evening sector and as a result give rise to the eastward electrojet. However this requires further investigation, ideally as part of a study encompassing all evening sector features.

The analysis of the effects of induced currents in the sea, in Appendix B, shows that they can sericusly affect the magnetic bays in the D component. This is important because D bays are often used to deduce characteristics of field-aligned currents so neglecting the induced current effect would produce erroneous conclusions.

The study of power system problems (Appendix C) demonstrated that local features affect the magnitude of the disturbance but that polar substorms are the fundamental cause of the disturbance.

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APPENDIX A: THE EFFECT OF FXI ON BLACKOUT OCCURRENCE

(sub. to the Journal of Atmos. and Terr. Physics, Oct. 1979)

A.1. Introduction

The occurrence of blackout on ionosondes has long been used as an indication of enhanced absorption (eg. Thomas and Piggott, 1960). Analysis of riometer and ionosonde records from Halley Bay (75.5°S, 26.6°W) for 1974, allows comparison between actual measurements of absorption and the ionosonde data. At Halley Bay the diurnal variation of blackout occurrence peaks at 06.00 local time in contrast to the occurrence of absorption at 27.6MHz>1dB which has a maximum at 14.00 local time (fig A.1). Some workers believe that blackout is generally an indicator of smaller absorption events than those seen by the riometer, and that fig A.1 indicates that small absorption events, in general, occur at a time shifted relevant to the time of large absorption events (Piggott, private communication, 1979).

Blackout occurs when the absorption at the highest frequency at which echoes are received exceeds the threshold level of the ionosonde. The highest ordinary component echo from the F region is foI, while the highest extraordinary component echo is fxI. Normal observatory practice is to scale only fxI but foI can easily be obtained from the relation

$$fxI = foI + f_L/2$$

The value of fxI (and foI) is affected by diurnal and seasonal F region variations and by the occurrence of spread F. (for full explanations of terms fxI and foI see Piggott and Rawer, 1972). This study examines the effect of variations in fxI on the occurrence of blackout in order to assess the reliability of blackout occurrence as an indicator of enhanced absorption.

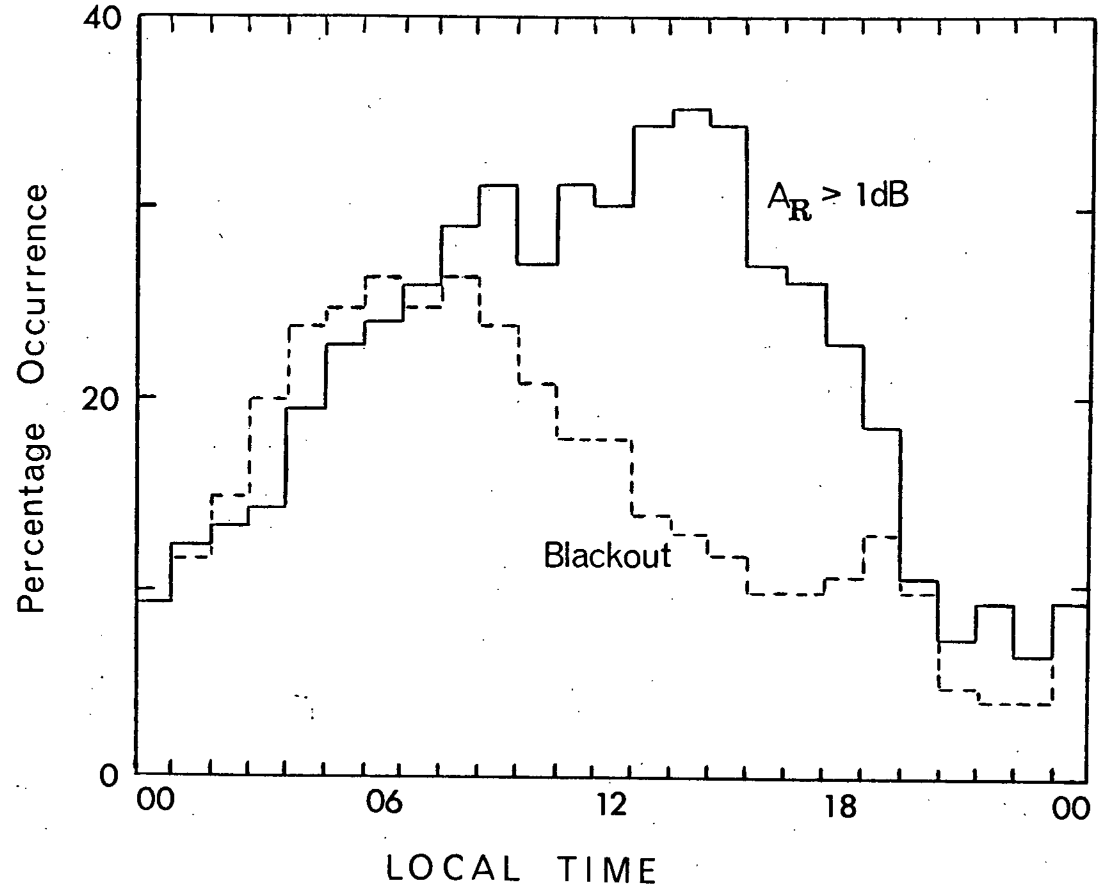

fig A.1. Comparison between the occurrence of blackout on the ionosonde and the occurrence of absorption at 27.6MHz > 1dB as seen by the riometer in 1974 at Halley Bay, Antarctica.

A.2. Conditions Required For Blackout

Absorption at Halley Bay is principally produced by D region ionisation above 70km, except during PCA events which are comparatively rare during sunspot minimum, the time considered (Piggott and Hurst, 1976). Hence the frequency dependence of the absorption can be expressed by an inverse square law relationship (Piggott, 1953). An absorption index, A, for a single path can therefore be defined in terms of the absorption, L, measured at any frequency f:

$$A = L(f+f_L)^2$$

Where f_L is the electron gyro-frequency, and the sign is positive for ordinary rays and negative for extraordinary rays.

Thus under conditions that produce an absorption index, A, the absorption suffered by ordinary and extraordinary rays of frequency, f, in passing once through the D region will be respectively

$$L_o = A/(f+f_L)^2 \qquad L_x = A/(f-f_L)^2$$

Ionosonde signals, reflected by the E or F region, pass twice through the D region and so the absorption suffered by the o and x components will be

$$L_o = 2A/(f+f_L)^2 \qquad L_x = 2A/(f-f_L)^2$$

The minimum frequency at which an echo is seen on the ionosonde will occur where the absorption, L, at that frequency equals the threshold level of the ionosonde, T.

For ordinary rays fmin is given by

$$fmin_o + f_L = (2A/T)^{0.5}$$

For extraordinary rays fmin is given by

$$fmin_x - f_L = (2A/T)^{0.5}$$

Combining the above two equations shows that

$$fmin_o = fmin_x + 2f_L$$

Thus when fmin is close to the top echo frequency seen on the ionosonde, that top frequency will be due to an ordinary ray, not an extraordinary ray: ie. the top frequency will be foI not fxI.

Therefore blackout will occur when fmin exceeds the ordinary component top echo frequency. That is when

$$fmin > foI$$

Substituting for fmin , from equation (v) gives

$$(2A/T)^{0.5} > foI + f_L$$

FoI is not usually scaled and so it is preferable to use fxI. Using equation (i), the above inequality can be written as

$$(2A/T)^{0.5} > fxI + f_L/2$$

Thus the requirement for blackout can be expressed as

$$A > 0.5T(fxI + f_L/2)^2$$

A.3. Blackout Occurrence At Halley Bay

At Halley Bay the electron gyro-frequency, f = 1.2MHz.)p by comparing fmin values with ricmeter measurements of absorption as described by Kressman and Piggott (1976), the threshold level of the ionosonde at Halley Bay compared to the amplitude of an unabsorbed reflection was calculated to be 80 + 10 dB. This value was then used in expression (xi) to calculate the absorption index, A, required to give blackout for different values of fxI as well as the absorption values, L_R, for a riometer operating on 27.6MHz. (table A.1).

FxI (MHz)	1	2	3	4	5	6
A (dB)	100	270	520	850	1250	1750
L_R (dB)	0.12	0.32	0.62	1.02	1.50	2.10

table A.1. Absorption index, A, required to give blackout for different values of fxI at Halley Bay, calculated from the equation: $A > 0.5T(fxI+f_L/2)^2$, with T=80dB and f_L=1.2MHz. Also shown is the associated value of absorption at 27.6MHz, L_R, calculated from $A=L_R(27.6+f_L)^2$.

A.4. Comparison Between Ionosonde And Riometer Measurements

Riometer and ionosonde measurements are not always comparable in individual cases. The riometer gives a measure of the average absorption within the acceptance cone of its antenna, about 60°, whereas the ionosonde for a near vertical reflection is affected only by the absorption which is present in a much smaller angle from the vertical. Also the ionosonde sometimes receives echoes from oblique angles and in such cases blackout would not be recorded. Both these factors can be expected to cause some scatter in the relations between riometer and ionosonde measurements when the absorbing zone is not uniform. Also during blackout, by definition, no echoes are received by the ionosonde, and so actual values of fxI are not available. Therefore monthly median values, which are available for each hour, will be used instead of individual fxI values.

As a first test to determine the effect of fxI on blackout occurrence, because enhanced absorption occurs principally at the equinoxes, the median fxI values for the equinoctual months were used. Comparison between the average median fxI value (fig A.2) and table A.1 shows that at 06.00 local time blackout should occur when L_R>0.9dB while at 14.00local time blackout should be produced when L_R>1.9dB. Examination of all 1974 riometer and ionosonde records for 06.00 local time shows that absorption at 27.6MHz>1dB is accompanied by blackout in 90% of cases. A similar study shows that at 14.00 local time absorption at 27.6MHz>2dB is accompanied by blackout in 85% of cases.
tests show that these results are significant at the 0.1% level. This indicates that ionisation producing L_R> 1dB is usually

sufficient to prcduce blackout at 01.00 local time but that at 14.00 ionisation producing $L_R > 2$dB is required.

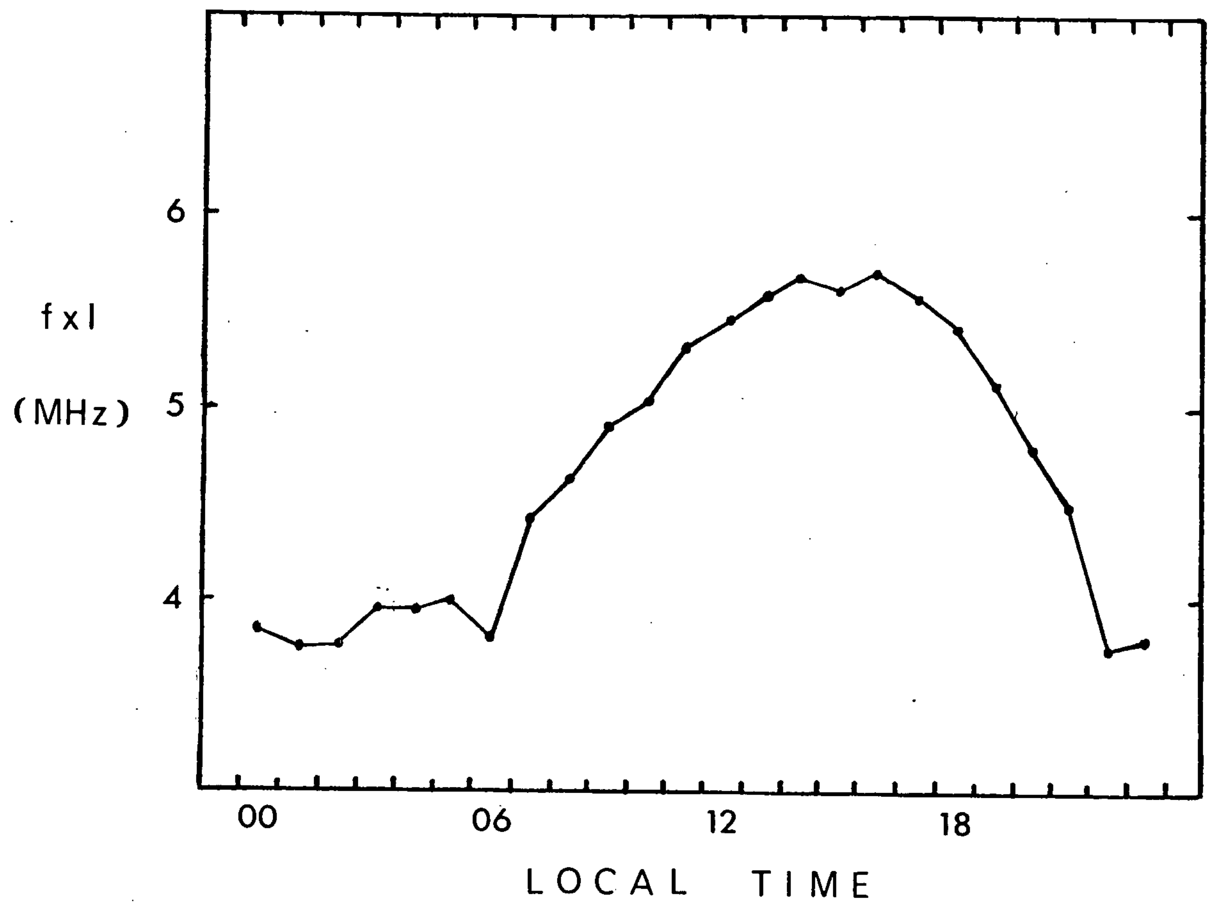

Fig. A.2. The median value of fxI, normally the highest frequency at which echoes are seen on the ionosonde, for the equinoctual months of 1974.

As a further check on the effect of fxI, the median values of fxI for each month in 1974, were used to determine the equivalent absorption at 27.6MHz that would be expected to give blackout. The actual riometer records were then examined to determine the number of times at each hour that L_R exceeded these values. Comparison of this "predicted" blackout occurrence with the actual blackout produced a goodness of fit to a straight line of 0.82. This is reflected in the close similarity of the diurnal variation of occurrence of "predicted" and actual blackout as shown in fig A.3.

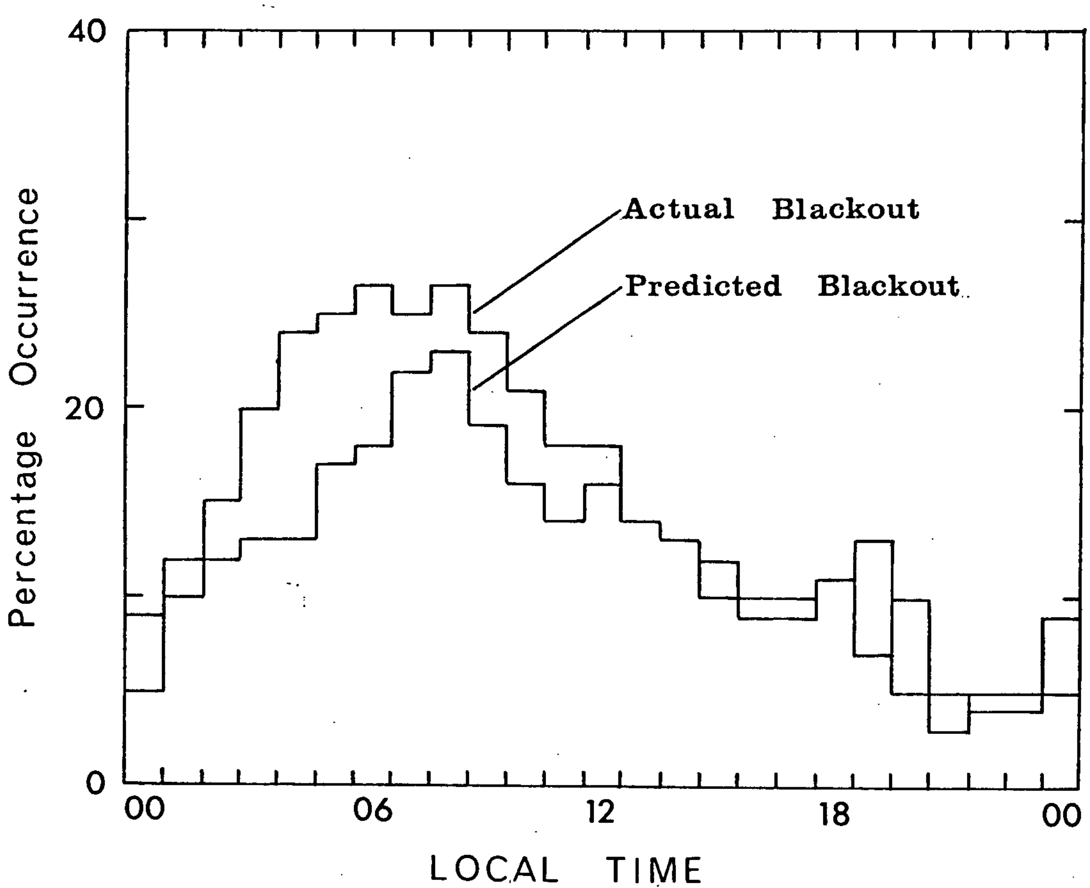

Fig. A.3. Percentage occurrence of blackout 'predicted' by comparing riometer records with the absorption index $A = 0.5T(fxI + f_L/2)^2$ where T is the threshold level of the ionosonde.
Together with the percentage occurrence of actual blackout

A.5. Discussion

It is generally accepted that ionosonde fmin values provide a more sensitive measure of small absorption events than a riometer. However table A.1 shows that the absorption required to produce blackout is heavily dependent on the value of fxI. Thus statistics of blackout occurrence are unreliable as a guide to the occurrence patterns of enhanced absorption.

Diurnal changes in fxi, at Halley Bay, seriously affect the occurrence pattern of blackout. As shown in fig A.1, the peak occurrence of blackout is considerably earlier than the peak occurrence of absorption > 1dB as detected by the riometer. This difference is adaquately accounted for when variations in fxI are taken into account (fig A.3). Thus there is no evidence from Halley Bay blackout results to indicate that smaller absorption events occur earlier than large absorption events.

Seasonal variations in fxI also affect the occurrence of blackout. In 1974, enhanced absorption at Halley Bay was most frequent at the equinoxes and there was a correspondingly high occurrence of blackout. However during the winter, although enhanced absorption was comparatively rare, there was considerable blackout. This was often associated with only 0.5dB absorption at 27.6MHz because fxI values were usually below 3MHz. Conversely during the summer, because of high values of fxI (about 6MHz) there was little blackout despite significant occurrence of enhanced absorption.

Appendix AA: The Threshold Level Of The Halley Bay Ionosonde

Assuming an inverse square law relationship it has been shown that for ordinary rays

$$fmin + f_L = (2A/T)^{0.5}$$

Which can be written

$$A = 0.5T(fmin + f_L)^2$$

Thus in a plot of A versus $(fmin+f_L)^2$ the slope, T/2, gives a measure of the threshold level of the ionosonde. Following the method of Kressman and Piggott (1976), I used fmin values, from December 1976, for 14.00 local time, a time when no added attenuators were in use. These fmin values were plotted against absorption index values derived from riometer measurements (fig A.4). The slope, T/2, of the line drawn by eye through the points, is 41dB. Thus the threshold level of the ionosonde at Halley Bay is taken as

$$T = 80 \pm 10 \text{ dB}$$

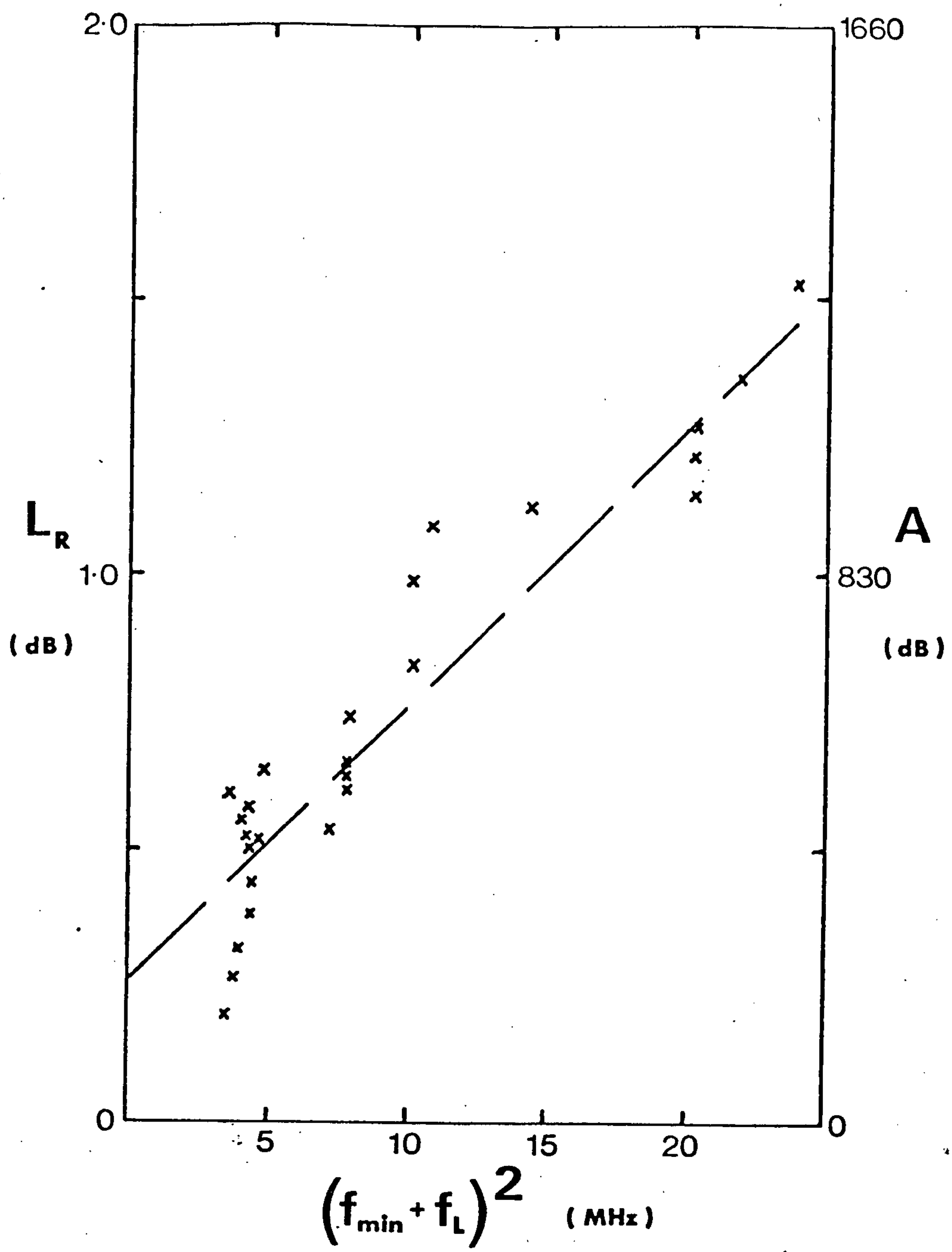

fig A.4. Relation between riometer absorption measurements, the equivalent absorption indices, and fmin for 14.00 local time, December 1976.

APPENDIX B: THE EFFECT OF INDUCED CURRENTS IN THE SEA ON MAGNETIC BAYS OBSERVED AT A COASTAL OBSERVATORY (pub. in the Journal of Atmos. and Terr. Physics, May, 1978)

B.1. Introduction

The magnetic signature of a polar substorm is a departure of the magnetic field from its normal value, by several hundred gammas lasting for an hour or so and normally referred to as a magnetic bay. Such magnetic bays are primarily due to an intense current flowing along the auroral oval, called the auroral electrojet (see review paper by Anderson and Vondrak, 1975). Near the westward electrojet, a negative bay is observed in the horizontal component of the magnetic field, H in the vertical component, Z, positive bays are observed to the north of the westward electrojet while negative bays are observed to the south. The characteristics of H and Z bays are well established but there remains considerable confusion about the bays in the east-west component, D, and most authors have in the past ignored them.

In a statistical study of bays observed at Scandinavian stations Harang (1946) showed that negative bays in H were usually acconpanied by an eastward deflection in D. Such bay events would indicate a magnetic disturbing vector that pointed south-east throughout the night hours. Later workers, however, found cases where the disturbing vectors were directed to the south-west in the morning sector (Akasofu and Meng, 1969). The observed distribution of disturbing vectors is often expressed in terms of an equivalent current system in the ionosphere which, as Akasofu (1968) points out, is a mathematically correct method of representation. The actual current system is now believed to involve field-aligned currents which connect the ends of the electrojet to the magnetosphere where the circuit is completed by the current generator. (the latter is believed either to involve short-circuiting of part of the magnetotail current (e.g. McPherron et al., 1973), or connection to the partial ring current (Bonnevier et al., 1970). This current system is consistent with earlier models since it produces the same magnetic disturbance on the ground as a purely ionospheric current system (Fukushima, 1970). According to Kisabeth and Rostoker (1971), bays in the H and Z component are produced by the electrojet itself whereas the bays in the D component are caused by the field-aligned currents. Rostoker (1972), constructed latitude profiles of the magnetic disturbance produced by an electrojet and reported that the D bay configuration is determined by whether the meridian of the latitude profile is east or west of the central meridian of the electrojet. For the simple model, in which the current flows down the field lines on the morning side, along the auroral oval and back up to the magnetosphere on the evening side, the sign of the D bay would be expected to change as the station moved from east to west of the central meridian of the electrojet. However, a more complex model, recently proposed by Kamide et al (1976), which is composed of pairs of field-aligned currents, suggests that the sign of the D bay should not change in keeping with Harang's results.

At Halley Bay, Antarctica (75° S, 27° W), a change in the D bay with position of the station relative to the electrojet, occurs in only a few cases and the D bays are predominantly of the same sign. However, there is another factor which can effect magnetic bays recorded at coastal stations, namely currents induced in the neighbouring sea by the auroral electrojet. Neglecting the effect of such currents may lead to incorrect conclusions about the form of the ionosphere magnetospheric current system. This paper examines the influence of induced currents and demonstrated the effect they can have on the magnetic bays observed.

B.2. Induced Currents

An electrical current system in, or above, the ionosphere, such as the auroral electrojet system, will induce currents in the earth. The intensity of the induced currents will be much greater in the oceans than in the continental land mass because the conductivity of sea water (3-4 $ohm^{-1}\ m^{-1}$) is several orders of magnitude greater than that of rock (10^{-1} - 10^{-4} $ohm^{-1}\ m^{-1}$). Ice has a conductivity of $1\text{-}2.10^{-5}$ $ohm^{-1}\ m^{-1}$, so induced currents in the polar ice or adjoining ice shelf will also be insignificant compared with those in the ocean.

An induced current near the surface will reduce the observed Z disturbance, ΔZ, and increase the observed H disturbance, ΔH. If the depth of the region where the induced currents are situated is sufficiently great, ΔZ will be reduced to zero and H will be doubled. The skin depth, ρ, at which the induced current density drops to 1/e of its surface value is given by Garland (1960) as $\rho = \frac{1}{2\pi}\left(\frac{T}{\sigma}\right)^{1/2}$

where T is the period, in seconds, of a sinusoidal inducing current and σ is conductivity, in e.m.u. For T = 1000s, corresponding to the duration of a short bay, and σ = 4 ohm m (4×10^{-11} e.m.u.) the skin depth is about 8 km. Using a formula which takes intc account the effect of a non-uniform inducing field upon skin depth, Price (1967) calculated the effects of induced currents on the H and Z parameters measured at the surface of an infintely large ocean of depth D, Table B. 1.

D, km	0.5	1	2	3	4	5
$\Delta H/\Delta H_0$	1.56	1.71	1.83	1.88	1.91	1.93
$\Delta Z/\Delta Z_0$	0.44	0.29	0.17	0.12	0.09	0.07

Table B.1. The effects of induced currents on H and Z variations at the surface of an ocean of depth D. The wavelength of the inducing field is taken as 1000km, the conductivity, σ as 4.10^{-11} e.m.u., and the period T as 1000s (after Price, 1967).

Clearly the ratios of the resultant fields, to the inducing fields, $\Delta H/\Delta H_o$, and $\Delta Z/\Delta Z_o$, are significant even for depths of 0.5km. Therefore sizeable induced currents are expected to occur in the Weddell Sea which will affect the magnetic disturbances at Halley Bay. Using measurements from drifting ice islands in the Arctic Ocean, Zhigalov (1960) found that the ratio $\Delta Z/\Delta H$, of the magnetic disturbances in the Z and H components, decreased considerably as the sea depth increased (Fig. B.1.) due to the effect of induced currents.

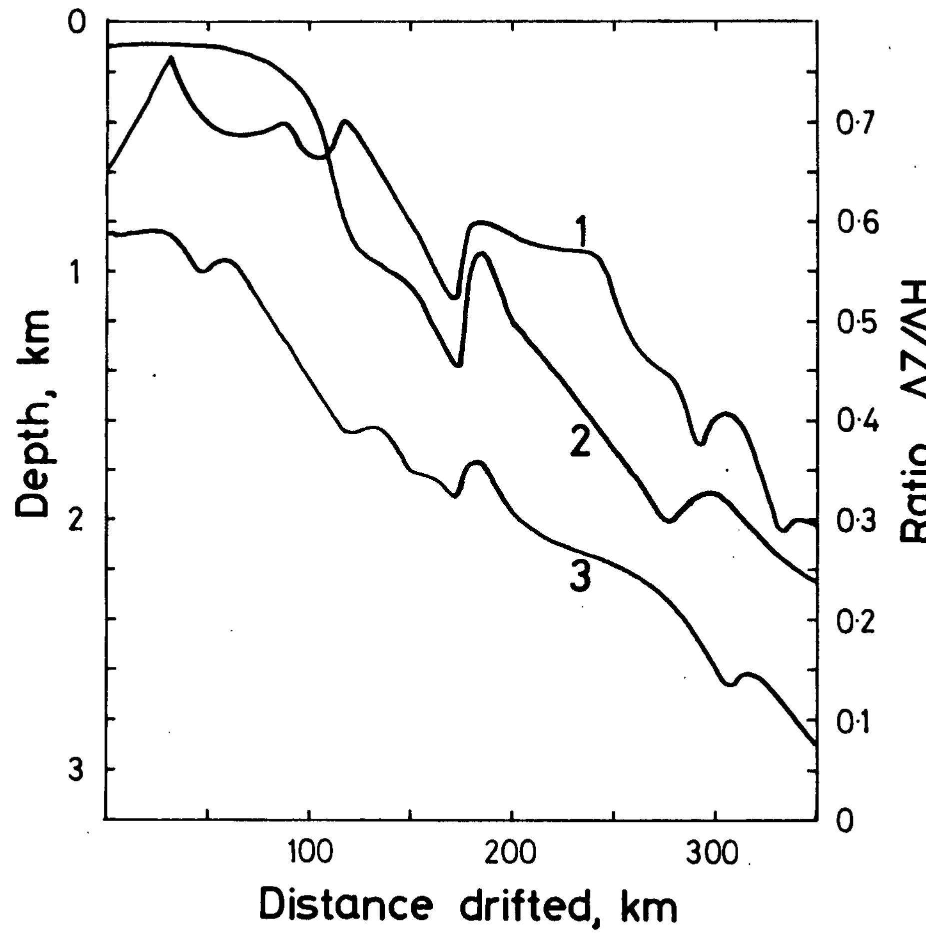

Fig. B.1. Values of the ratio $\Delta Z/\Delta H$ and of ocean depth of drifting ice station North Pole 6 (after Zhigalov, 1960). 1: Ocean depth, 2: Mean value of $\Delta Z/\Delta H$ for all hours of day 3: Mean value of $\Delta Z/\Delta H$ for variations of period 10 min.

B.3. Analysis Of Magnetic Bays

Quiet arcs, which define the position of the auroral oval (Feldstein, 1963), are seen well to the south of Halley Bay, at angles of elevation below 7 (Seivwright, 1969). Thus it should be possible at Halley Bay to interpret magnetic bays in terms of an equivalent line current flowing along the auroral oval, although such an approach would not be valid at a station close to the electrojet.

Of 294 bays examined, during sunspot minimum (1974-75) at Halley Bay, 222 featured a negative bay in the H component and a positive bay in the Z component. These bays occurred between 22.00 LZT and 06.00 LZT and are compatible with a westward electrojet to the south of the station. The other major class of bays was consistent with an eastward electrojet to the south and contained 48 examples occurring between 16.00 LZT and 21.00 LZT. For both classes, bays should be evenly distributed between those caused by an electrojet to the east of the station and those caused by an electrojet to the west. As the electrojet is fixed in space while the Earth rotates underneath, the position of the station relative to the electrojet changes steadily with local time. Therefore for bays with a symmetrical distribution of occurrence, the station should, on average, cross the central meridian of the electrojet at the median time of occurrence,. For a westward electrojet this is at 02.00 LZT and for an eastward electrojet it is near 18.00 LZT. As mentioned, the sign of the D bay should change at these times, however, of the 222 bays produced by a westward electrojet, all but 6% featured a positive bay in the D component. The negative bays in D that occurred were evenly distributed through the period of negative H bays. For the 48 bays produced by an eastward electrojet, all of the D bays were of the same sign. For each magnetic bay disturbance the ratio of the H and D bays, ΔH and ΔD, was used to define the angle of azimuth (tan $\Delta D/\Delta H$) of the equivalent disturbing vector. A disturbing vector produced by an electrojet along the auroral oval should lie normal to the oval, however, both classes of bays produced disturbing vectors rotated 20°-30° anticlockwise from the normal. This is illustrated in Fig. B.2 which, taking the azimuth of midpoints of quiet arcs as the normal to the oval, shows that the disturbing vectors for the bays produced by a westward electrojet point 20°-30° east of the normal.

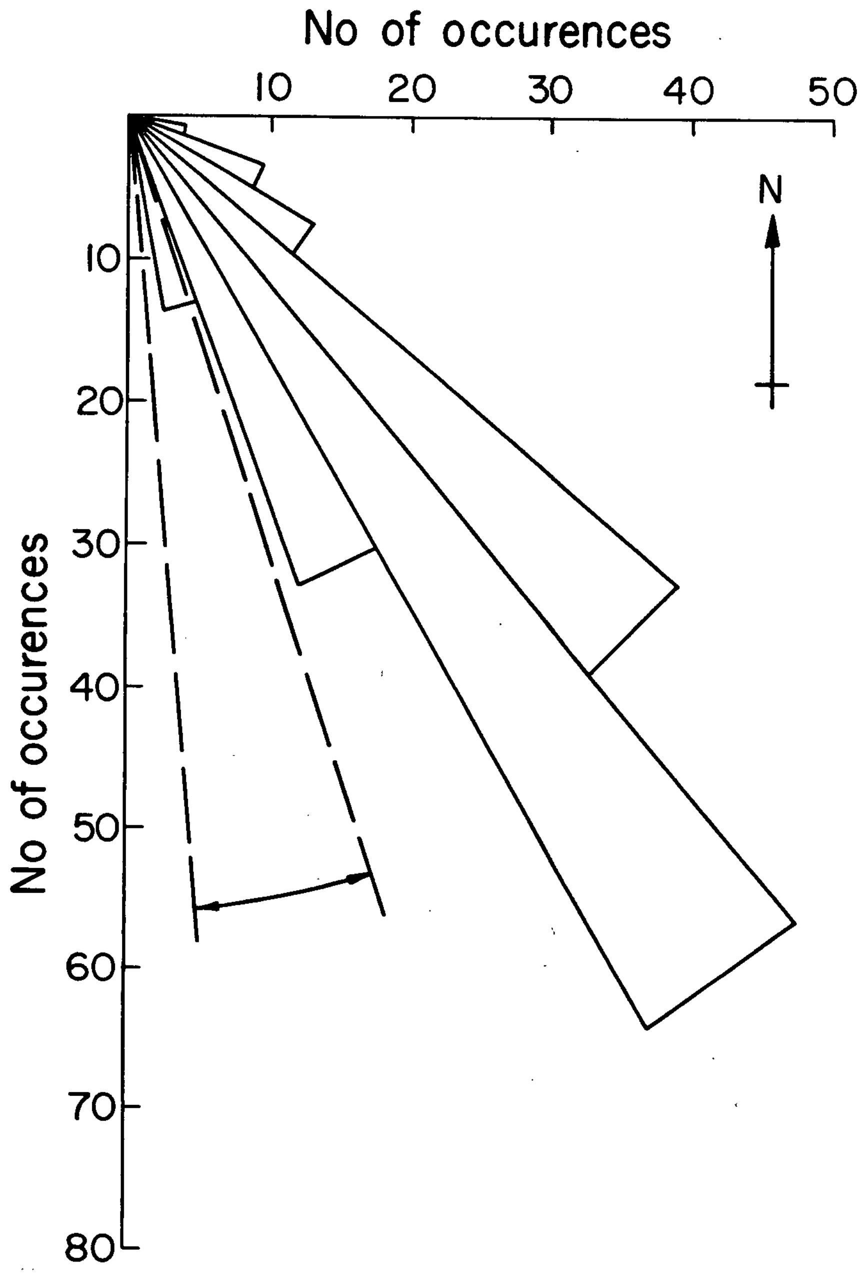

Fig. B.2. Distribution in azimuth of disturbing vectors responsible for magnetic bays at Halley Bay, 1974-75. The dotted lines represent the range of position of the normal to the oval, as given by the mean azimuth of quiet arcs (after Sievwright,1969).

B.4. Discussion

Parkinson (1962), in a study of disturbing vectors, observed at statons throughout the world, found that a large proportion of them pointed in the direction of the nearest deep ocean. Induced currents increase as the depth of the ocean increases so it is reasonable to assume that near the coast the currents are deflected to follow the contours of the ocean floor. Price (1967) notes that there is probably an important coast effect extending over the shallower parts near the edge of an ocean. The effect of induced currents on magnetic variations near the California coast was studied by Schmucker (1964) who concluded that the currents flowed parallel to the coast and tended to concentrate near the edge of the continental shelf. Halley Bay is a coastal observatory, so the most important currents will flow in the sea. A bathymetric contour map of the Weddell Sea (Fig. B.3) shows that the contour lines immediately adjacent to Halley Bay lie at an angle of azimuth of approximately 35°, as does the coast. The actual effect of the coast on the intensity of the induced currents is uncertain, however an assessment can be made by assuming that they produce their maximum effect, i.e. doubling of the horizontal disturbance.

During the night the mean azimuth of the mid-point of quiet arcs, θ, varies smoothly between 162° and 175°, from 18.00 LZT to 08.00 LZT (Sievwright, 1969). The disturbing vector solely produced by the electrojet would be expected to lie between these values. Assuming that the induced currents flow parallel to the contour lines, i.e. at an angle of azimuth $\gamma = 35° \pm 5°$, the expected azimuth of the observed disturbing vector α, can be calculated. The two limit cases, when $\theta = 162°$ with $\gamma = 30°$ and when $\theta = 175°$ with $\gamma = 40°$, give values for α of 141° and 153° respectively. This is consistent with the median azimuth of the actual disturbing vector observed which lies between 140° and 150°.

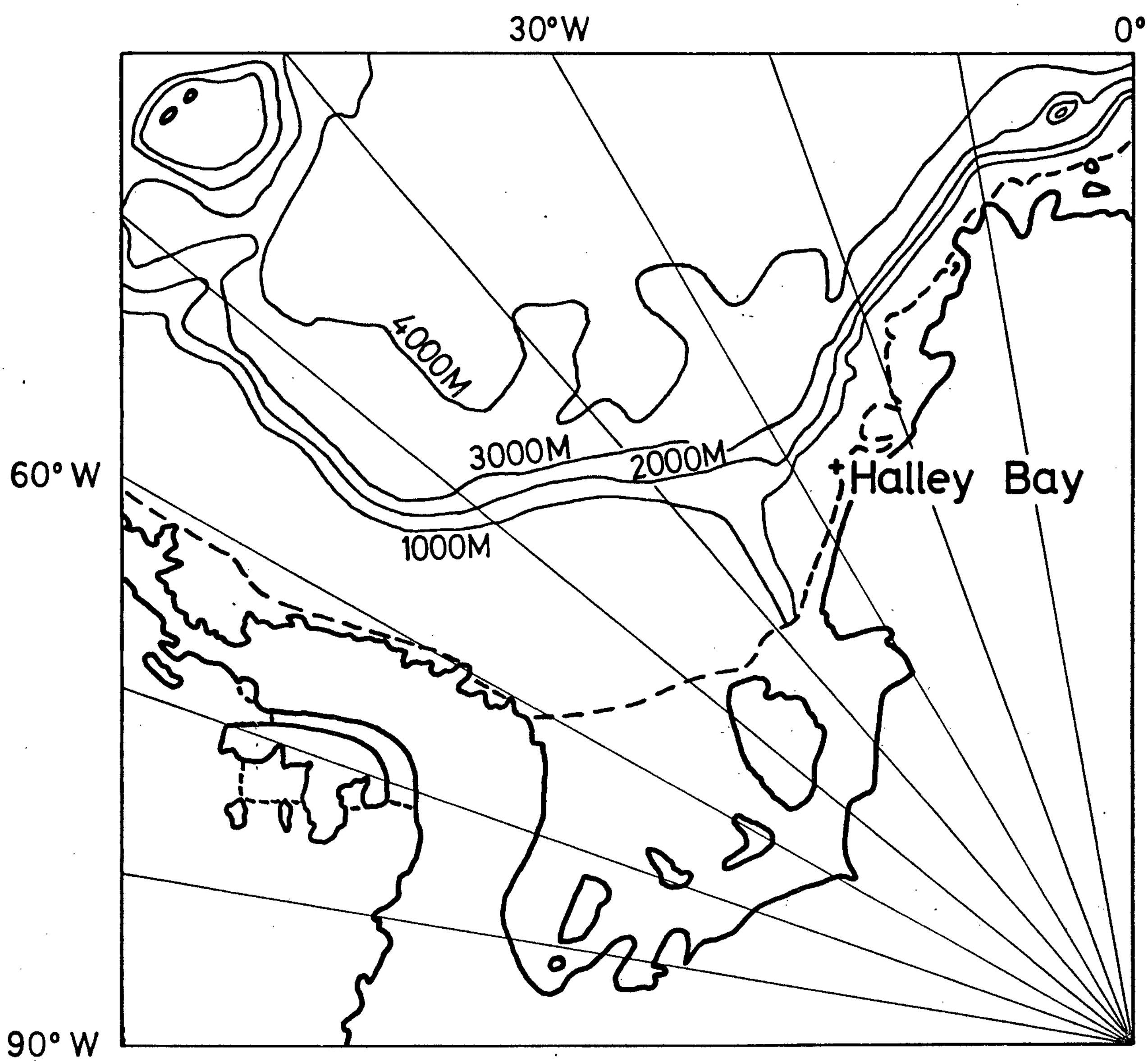

Fig. B.3. Bathymetric chart of the Weddell Sea adjacent to Halley Bay (after Heazen et al, 1972).

B.5. Conclusion

Induced currents in the sea can have a significant effect on magnetic bays at coastal observatories. The magnetic bays at Halley Bay correspond to an electrojet to the south of the station modified by the effects of induced currents in the adjacent ocean. These currents flow parallel to the edge of the continental shelf and, because if its alignment, have a greater effect on bays in the D component than on those in H. It is possible that induced currents have a more significant effect on D bays than field-aligned currents at other coastal observatories. Whether this occurs depends on the relative magnitudes of the D perturbation arising because of the coastal effect, Dc, and the normal perturbation, Dn, that would otherwise be observed. Any effects of field-aligned currents (such as the reversal in the D bays, proposed by Rostoker (1972)) would be reflected in Dn and whether or not they were observed would depend on the ratio Dc/Dn. The magnitude of Dc/Dn is dependent on the orientation of the coastline: being small for an E-W coast and large when the coast runs N-S. Thus for coastal observatories the alignment of the coast and the effect of induced currents should be investigated before using the magnetic bays to infer overhead current systems. For instance Harang's (1946) analysis is of magnetic disturbances at Scandinavian observatories which may be influenced by induced currents in the sea.

APPENDIX C: THE PROBLEM OF SOLAR INDUCED CURRENTS

(presented at the International Solar-Terrestrial Predictions Workshop, Boulder, April 1979)

C.1. Introduction

Power system disturbances have been known to occur during geomagnetic storms for nearly 30 years. The disturbances are due to quasi-d.c. Currents, induced in the earth by geomagnetic field variations, flowing through transformer neutral-ground connections into the power system. Because the geomagnetic storms originate with disturbances on the sun the quasi-d.c. currents were called Solar Induced Currents (SIC), however recently the more appropriate term Geomagnetically Induced Currents (GIC) has also been used.

The level of interest of electrical engineers in geomagnetic phenomena shows a marked correlation with the sunspot cycle! Interest was first aroused by power system disturbances during the geomagnetic storm of March 24, 1940 (McNish, 1940) and extensive SIC effects were noted during the storm of February 1958 (Slothower and Albertson,1967) and the storm of August, 1972 (Albertson et al , 1974). By the time of the last sunspot maximum (1968-1970) a major research effort had been mounted under the sponsorship of the Edison Electric Institute, and the results of the study (Albertson et al, 1973; Albertson and Thorsen, 1974) represent the principle contribution to our knowledge of SIC.

Significant contributions have been made in parallel fields by Anderson et al (1974), who studied the effect of geomagnetic disturbances on cable communication systems, and by Campbell (1978) who analysed the induced currents in the Alaska pipeline. Campbell used the geomagnetic activity index, Ap, to determine the expected levels of induced currents in the Alaska pipeline, and this technique was adapted by Goddard and Boerner (1978) to the SIC problem. Apart from this, there has been an increased awareness of the effect of geomagnetic phenomena on man-made systems (e.g. Lanzerotti, 1978) and of the effect of power system radiation on the space environment (Helliwell et al, 1975; Hayashi et al, 1978) but little work specifically related to the problem of SIC.

The facts to date about SIC are that they fluctuate with a period of several minutes, ie. are quasi-d.c. compared to 60Hz; and their occurrence correlates with that of geomagnetic storms. Areas of igneous rock geology give rise to higher SIC values and anamously high SIC are experienced at a location in Newfoundland (Albertson and Thorsen, 1974). SIC are generally more severe at higher latitudes and because of this are believed to be due to the geomagnetic disturbances produced by the auroral electrojet. Possible values of the surface electric field (and consequent levels of SIC) due to the auroral electrojet were calculated by Albertson and Van Baelen (1970) and shown to be consistent with observed SIC. Albertson and Van Baelen also showed that SIC should be greater in power lines running E-W compared to those running N-S, although no observation of this effect in practice has been reported in the literature.

The effects of SIC on electric power systems and the prediction needs of the power industry have been well covered by Albertson and Thorsen (1974) and Albertson and Kappenman (1979). The problem confronting geophysicists is to explain the production of surface electric fields by geomagnetic disturbances and combine the electric field information with power system parameters to produce a quantitative understanding of SIC. This knowledge should then be coupled with improvements in predicting geomagnetic disturbances to obtain forecasting of SIC levels in any particular power system.

C.2. Production Of Surface Electric Fields

Geomagnetic disturbances induce currents in the earth and the potential drop produced by the flow of these currents can be detected at the surface as an electric field E, also called the earth surface potential, ESP. In the simplest case the geomagnetic disturbance can be considered as a downward propogating wave of frequency ω, incident on a homogeneous earth of conductivity σ_1. The relationship between the electric and magnetic fields at the surface is given by

$$\frac{E_x}{H_y} = \left(\frac{j\mu_0\omega}{\sigma_1}\right)^{1/2}$$

and the depth of penetration of the wave to 1/e of its surface value is the skin depth

$$\delta_1 = \frac{1}{\sqrt{2\pi\sigma_1\omega}} = \frac{1}{2\pi}\sqrt{\frac{T}{\sigma_1}}$$

It is obvious that the skin depth increases with the period of the geomagnetic variation and so, in a real earth, conductivity changes with depth will affect the frequency response of the function Ex/Hy. This was recognised by Kato and Kikuchi (1950) and Kato and Yokoto (1953) who expounded the initial theory which, with further developments by Cagniard (1953), led to the technique now known as the magnetotelluric method.

The magnetotelluric method uses measurements of Ex/Hy versus frequency, , to determine the conductivity structure of the earth, usually by comparison of the experimental results with results from calculations for a range of earth models. In the SIC study we are concerned with the reverse prcblem of (hopefully) knowing the conductivity structure below the area concerned and wishing to calulate the surface electric field Ex produced by geomagnetic variation of magnitude Hy and frequency . However, the mathematical analyses of induced current developed for magnetotelluric studies (e.g. Price, 1967; Jones and Price, 1970) are still applicable to the SIC problem.

The theoretical treatment of induced currents developed by Cagniard (1953) has been extended by later workers to include effects due to the scale of the source field. For example, the formula produced by Wait (1962) for a 3 layer earth with layer thicknesses h_1, h_2 and ∞, and conductivities σ_1, σ_2 and σ_3 is

$$\frac{E_x}{H_y} = \left(\frac{j\mu_0 \omega}{\sigma_1}\right)^{\frac{1}{2}} (1-jB)^{-\frac{1}{2}} Q\left[(\sigma_1 \mu_0 \omega h_1)^{\frac{1}{2}}, \frac{\sigma_1}{\sigma_2}, \frac{\sigma_3}{\sigma_1}, \frac{h_1}{h_2}\right]$$

where the 1st term is the formula fcr a homogeneous earth of conductivity σ_1; the 2nd term includes the effect of the source size L, with $B = \delta^2/2L^2$; and the 3rd term contains the layered earth effects.

Price (1962) has argued that Waits formulation contains some simplifying assumptions, regarding the effect of the source size, that affect both Q and δ ; and there is still some confusion as to the true effect of the source size on the distribution of induced currents.

Determining the source size is also a problem. Campbell (1978) used Waits' (1962) formulation and derived the formula L=0.2T for the scale length, in km, of a geomagnetic variation with period T sec. This formula is based on the concept that a geomagnetic variation with a period of 24 hours has a scale equal to the circumference of the earth round the auroral zone, and that shorter period variations have a correspondingly smaller scale length. However if one considers a geomagnetic bay with T=1800 secs (30 min.), produced by the auroral electrojet, Campbell's formula gives a scale length equivalent to 7.5 degrees of longitude, whereas the auroral electrojet is known to extend up to 60 or more in longitude. The scale length of other geomagnetic variatons whose origin is attributed to the auroral electrojet (eg. Pc5 pulsations) are likely to be similarly underestimated by Campbell's formula.

Wait's formulation was applied to the SIC problem by Goddard and Boerner (1978) who used it to compute the probable frequency spectrum of electric field variations during a geomagnetic disturbance observed in Manitoba. This electric field frequency spectrum was then used for comparison with the frequency spectrum of Sic observed during the same disturbance (fig C.1). The spectra of the electric field and Sic should be highly correlated so the discrepancy shown in fig. C.1 is likely due to the calculation of the electric field. Goddard and Boerner used Campbell's formula for scale length and, as indicated above, this is an approximation and may produce a different frequency dependence than occurs in practice. The transfer function Ex/Hy used by Goddard and Boerner, as shown by figs C.1a and C.1b, is obviously independent of frequency; however, Campbell (1978) using the same formulation, but a different earth model, obtained a transfer function dependent on frequency which he approximated by the expression

$$\left[\frac{E_x}{H_y}\right] \times 10^6 = 3 \cdot 8 - 0 \cdot 92 \log T$$

thus the frequency dependence of the transfer function, Ex/Hy is very dependent on the earth model used.

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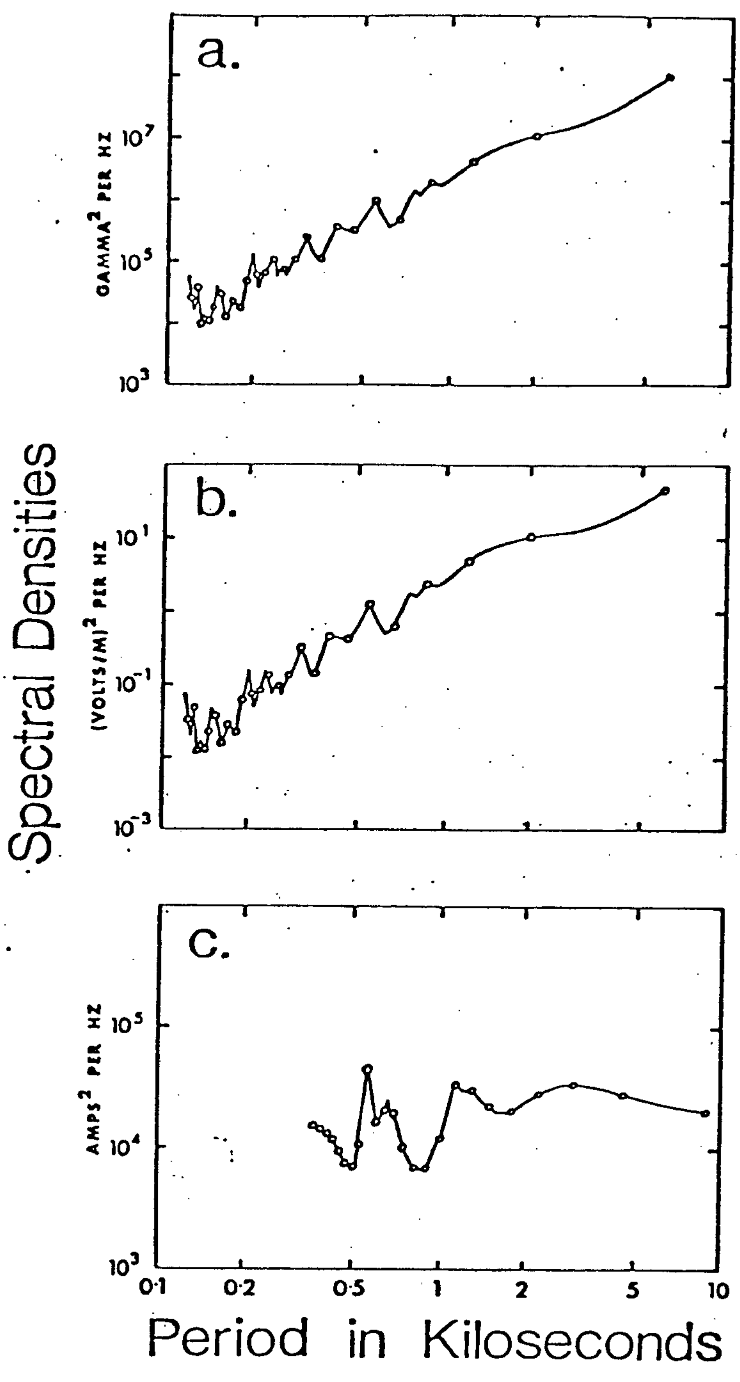


Fig. C.1. Average power spectra of (a) X component of magnetic field at Whiteshell, Manitoba, (b) expected Y component of surface electric field (calculated from the magnetic field variations), and (c) solar induced currents at LaVerendrye, Manitoba, (after Goddard and Boerner, 1978).

It should be remembered that the parameters $\sigma_1, \sigma_2, h_1, h_2$, etc used in the earth models are the mean values for an area comparable to the scale of the inducing field. The significance of the conductivities at depth is in how they affect the distribution of currents with depth and consequently the value of the surface current. The electric field at a particular location can then be determined by knowledge of the surface current and the local conductivity. Igneous rock areas are an example of the effect of local conductivity because their low conductivity, compared to other rock types, gives rise to higher electric fields and in consequence a greater probability of SIC problems. In Newfoundland the SIC magnitudes are too large to be simply accounted for by low conductivity and evidence is presented in section C.5 to show that the severity of SIC at Cornerbrook, Newfoundland is due to channelling of currents induced in the sea through a region adjacent to the power line.

C.3. System Considerations

The resistance of a power line , although typically a few ohms, is considerably greater than the resistance of the earth between the two ends of the power line. Thus it is applicable to calculate the surface electric field ignoring the presence of the power line, and then examine the effect of that electric field on the power line as a seperate problem. The electric potential applied across the ground points at the ends of a power line is simply the product of the component of the electric field parallel to the power line and the distance spanned by the power line. However the magnitude and distributuon of the currents, in the power system, produced by this earth potential depend on the relative magnitudes of the resistances of different parts of the system.

An analysis of part of the B.C. Hydro power system showed that for quasi-d.c. currents the system could be represented by a network of "line resistances" and "station resistances" as shown in fig C.2a. The station resistance is the resistance between the high voltage bus to which the power lines are connected and the ground mat of the substation. This station resistance could be simply the resistance of two transformers in parallel or, where autotransformers are used, a more complicated network of resistances as shown in fig C.2b. There is also a resistance between the station ground mat and "true earth", which is called the "station ground resistance", but this is usually small compared to the station resistance and can be neglected. The 3-phase power system can then be considered as 3 identical resistance networks in parallel and it is sufficient to consider one network only. This will enable calculations to be made of the quasi-d.c. currents expected in any part of the system; except that the current through the neutral-grcund connector of a transformer (where SIC are usually measured) will have currents from each of the 3 parallel networks and so will have 3 times the current calculated for an individual winding of the transformer. To determine the quasi-d.c. Currents in the network shown in fig C.2a equate voltages around loop I where I = 1,2,3,... n.

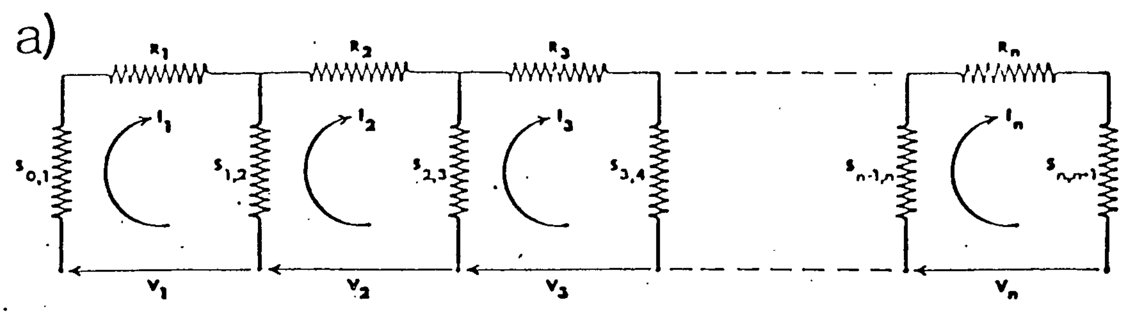
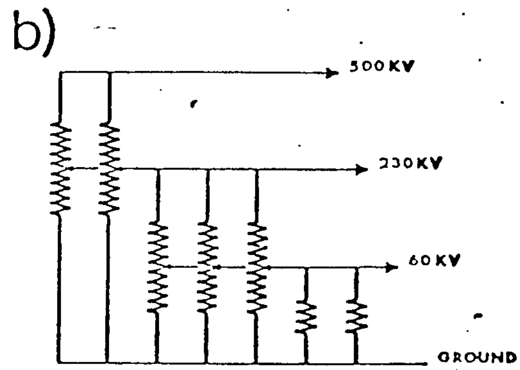


Fig. 2 a) 1-phase diagram of a power line, illustrating the network of line resistances R_1, R_2 . . . R_n, and station resistances $S_{0,1}$, $S_{1,2}$ . . . $S_{n,n+1}$.

b) Diagram of the components of the station resistance between a 500KV line and ground. (in this case at Williston substation in B.C.)



$$S_{i-1,i}\,(I_i - I_{i-1}) + R_i I_i - S_{i,i+1}\,(I_{i+1} - I_i) = V_i \tag{5}$$

Collecting terms gives

$$-S_{i-1,i}\,I_{i-1} + (R_i + S_{i-1,i} + S_{i,i+1})\,I_i - S_{i,i+1} I_{i+1} = V_i \tag{6}$$

For an isolated loop

$$I_i^{(o)} = \frac{V_i}{R_i + S_{i-1,i} + S_{i,i+1}} \tag{7}$$

and this can be taken as a first approximation to the solution of the general case, ie. equation (6). Employing an iterative method one can write

$$I_i = I_i^{(o)} + I_i^{(1)} + \ldots. \tag{8}$$

where the first order correction $I_i^{(1)}$ is given by

$$I_i^{(1)} = \frac{S_{i-1,i}\,I_{i-1}^{(o)} + S_{i,i+1}\,I_{i+1}^{(o)}}{R_i + S_{i-1,i} + S_{i,i+1}} \tag{9}$$

$$= \frac{1}{R_i + S_{i-1,} + S_{i,i+1}}\left\{\frac{S_{i-1,i}}{R_{i-1} + S_{i-2,i-1} + S_{i-1,i}}\,V_{i-1} + \frac{S_{i,i+1}}{R_{i+1} + S_{i,i+1} + S_{i+1,i+2}}\,V_{i+1}\right\} \tag{10}$$

Therefore

$$I_i = \frac{1}{R_i + S_{i-1,i} + S_{i,i+1}}\left\{V_i + \frac{S_{i-1,i}}{R_{i-1} + S_{i-2,i-1} + S_{i-1,i}}\,V_{i-1} + \frac{S_{i,i+1}}{R_{i+1} + S_{i,i+1} + S_{i+1,i+2}}\,V_{i+1}\right\} \tag{11}$$

Of the three terms in brackets in equation 11 the coefficients of V and V will be less than one and in the many cases in which line resistances are greater than the station resistances the coefficients will be small so that these terms can be ignored. The isolated loop approximation (equation 7) then represents a reasonable solution to the problem of calculating loop currents.

To determine the current through a particular station resistance $S_{i,i+1}$ it is necessary to consider the currents in loops I and i+1. It will be seen from equation 5 that the currents I_i and I_{i+1} tend to cancel each other at their common station, and so higher currents will be experienced in the lines than at the stations. The station resistance is actually comprised of a network such as in fig C.2b and the station current will naturally divide up between the different paths according to the relative resistances of the different transformers. Hence the current through an individual transformer will be a fraction of the current $I_{i+1} - I_i$ flowing to ground through the station. Fig C.2b also shows that where autotransformers are used higher currents will flow in the high voltage part of the winding than in the low voltage part.

C.4. Prediction Of SIC

If forecasting of SIC is to be improved it is no longer sufficient to describe SIC as being correlated with geomagnetic storms. It is desirable to ascertain which mechanisms are responsible for SIC and then prediction of these mechanisms can be related to prediction of SIC. The increase of SIC magnitudes with latitude, as mentioned earlier, points to the auroral electrojet as the cause of the field variations responsible and this has been assumed to be the case by most authors. However it is debatable whether the SIC seen at lower latitudes (eg. In the southern USA) are due to the auroral electrojet; and Anderson et al (1974) have presented evidence to show that magnetopause currents were responsible for the geomagnetic disturbance that so badly affected some communications systems in August 1972.

Resolution of the question would be greatly aided by knowledge of the diurnal occurrence pattern of SIC. Many geomagnetic phenomena have distinct average varitions of occurrence with local time which are well documented (e.g. Hartz and Brice, 1967). An equivalent representation is a local time perturbation profile such as that shown in fig 1 of Clauer and McPherron (1979). Their profile indicates that, for the current system specified (which involves a partial ring current), the maximum perturbation at mid-latitudes will occur in the afternoon. At auroral latitudes the major source of disturbances is the westward electrojet and this is located in the region extencing from 22.00 to 06.00 local time. Other disturbances can be similarly associated with a range of local times and the local times of occurrence of SIC should match those of the phenomena responsible. Also knowledge of SIC occurrence patterns at a number of locations could show whether or not the responsible phenomena change with latitude.

Should a SIC mechanism be identified which has a well defined local time dependence this knowledge would greatly aid SIC prediction. Even if SIC are produced by each and every type of geomagnetic disturbance they may show a local-time occurrence pattern simply because of the greater frequency of occurrence or greater magnitude of one specific mechanism. In the majority of cases such a local-time dependent probability of SIC occurrence could be used to provide several hours warning to electric utility operators of potential SIC problems.

Suppose, for example, that SIC are predominantly due to geomagnetic diaturbances caused by the westard auroral electrojet and so occur mainly between 22.00 and 06.00 local time. By continucusly monitoring this time zone, warnings of geomagnetic disturbances, in many cases, could be given before they had a significant effect in N. America. This method, of course, provides no warnings of disturbances that commence while N. America is in the 22.00-06.00 local time zone. Major disturbances will last for a day or more so the time zone specified could be considered as a "disturbed" zone,fixed w.r.t. the sun (fig C.3), through which N.America passes as the Earth rotates. Continuous observation of this "disturbed" zone effectively requires world-wide real-time monitoring of the surface geomagnetic field and relaying of the information to a centre in N. America. (A major undertaking).

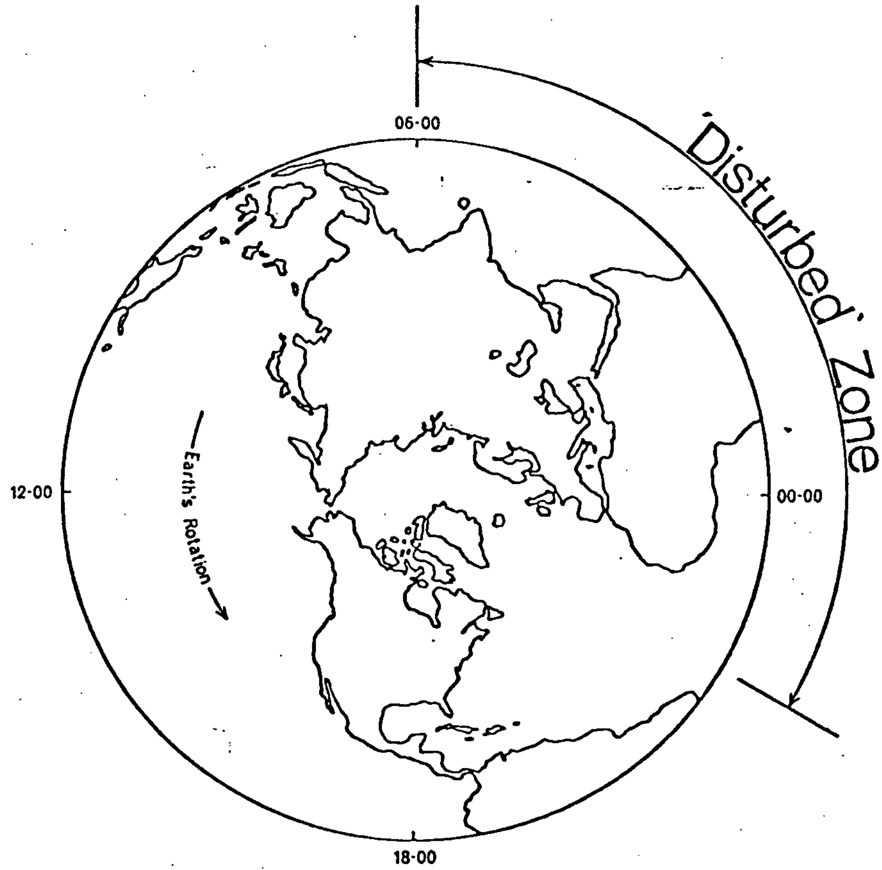


Fig. C.3. View of the earth from above the N. pole showing N. America being brought into a 'disturbed' zone by the earth's rotation.

However notification of disturbed conditions at European observatories could be used to provide forecasts, 4 hours or more in advance, of potential SIC conditions in N. America.

Even when gecmagnetic disturtances can be predicted, sections 2 and 3 have shown that there ate several factors limiting the translation of this to a forecast of the SIC magnitude to be expected at any particular location. Fortunately earlier experimental work has provided us with an empirical measure of the relative magnitudes of SIC at different locations on the form of Albertson and Thorsen's (1974) cumulative severity index (CSI). SIC predictions could be broadcast for a station with a CSI of 1 and, providing a suitable scale could be devised for the prdictions, the electrical utility operators at each location could multiply this by their own CSI to obtain a prediction relevant to their own system.

C.5. The Case Of Newfoundland

The severity of SIC at Cornerbrook, Newfoundland is too great to be simply another example of an igneous rock area and the case requires closer inspection. Fisher (1970) documented some of the problems due to SIC experienced with the Cornerbrook power system and he also reported that other electric utilities in Newfoundland did not experience noticeable SIC effects. The Cornerbrook power line is coincident with a zone joining carboniferous sediments to the salt water of the Gulf of St Lawrence (Wright, 1978); and Wright has suggested that this zone may be a conductive channel for telluric currents and be responsible for the great severity of SIC.

The intensity of induced currents in the oceans will be much greater than those on land because the conductivity of sea water (3-4 $ohm^{-1}\ m^{-1}$) is several orders of magnitude greater than that of rock ($10^{-1}-10^{-4}\ ohm^{-1}\ m^{-1}$). Price (1967) has shown that significant induced currents with a period of 15 minutes can be expected in depths as small as 500m; therefore, for shorter periods, sizeable currents can be expected in the depths of 300m typical of the continental shelf along the east coast of N. America. A theoretical analysis of induced currents near a conductivity discontinuity (such as a coastline) by Jones and Price (1970) shows that the currents should be concentrated on the high conductivity side of the discontinuity; and evidence for such an effect has been presented by Schmucker (1964) and Boteler (1978). Thus the indications are that high induced current densities occur along the east coast of N. America during geomagnetic disturbances.

Newfoundland and Nova Scotia represent low conductivity anomalies in the path of the coastal induced currents (fig D.4) and although the currents will tend to flow around the land the current across Newfoundland and Nova Scotia will be greater than the currents experienced on the continent proper. The currents will obviously concentrate across the narrowest parts of Newfoundland (see insets in fig C.4) and the surface electric field in these locations will thus be considerably greater than elsewhere on the island. Over distances for which the potential drop in the sea is small the coastlines on opposite sides of the island can be considered as equipotentials. Hence any power line running across the island and grounded on each shore will have the same potential applied across it during geomagnetic storms. Should such power lines present the same resistance to SIC the magnitudes of SIC would be the same in each power line. However shorter lines have lower resistances and consequently higher SIC levels. Thus the Cornerbrook power line is in one of the worst possible situations for experiencing SIC problems. Another location prsumably similarly affected is the Amherst area of Nova Scotia: a fact that may be significant considering the plans for power generation in the Bay of Fundy.

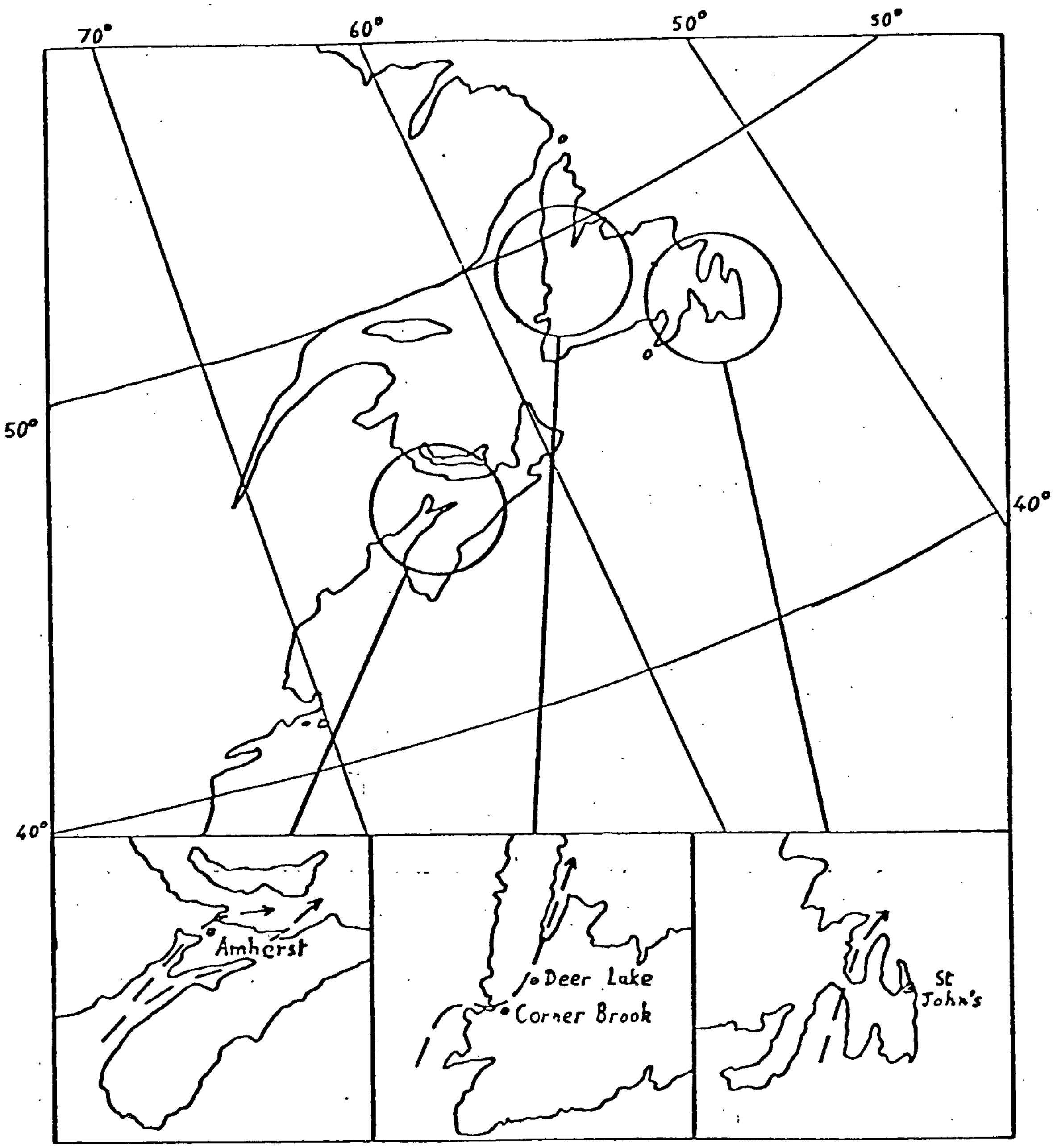


Fig. C.4. Map of the E coast of N. America (geographic coordinates). The insets show the channelling of induced currents across Newfoundland and Nova Scotia that is postulated to occur during geomagnetic disturbances.

C.6. Conclusions

It has been demonstrated that the magnitude of SIC at different locaticns on local conditions ans this is most marked in the case of the Cornerbrook power system in Newfoundland. At a particular location, the level of SIC in individual transformers (which is the critical parameter for SIC effects) cepends on the relative magnitude of the currents in the adjacent parts cf the power system as well as on the number and size of the transformers at the substation. The determination of the local time dependence of SIC occurrence would help identify the phenomena and could potentially enable several hours warning to be given of SIC conditions.