X-645-71-231
PREPRINT

NASA TM X-65596

ELECTRIC FIELDS IN THE IONOSPHERE AND MAGNETOSPHERE

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JUNE 1971

GSFC

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June 1971

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Review paper presented at the Advanced Study Institute on Magnetosphere-Ionosphere Interaction, Dalseter, Norway, April 14-23, 1971.

A B S T R A C T

Current techniques for measuring ionospheric and magnetospheric electric fields and existing measurements are reviewed. Considerable progress in understanding electric fields has been made in the auroral regions where fields originating basically from convection patterns in the magnetosphere and modified by ionospheric interaction have been detected by both the barium ion cloud and double floating probe techniques and compared against predictions. The anti-correlation of electric fields and auroral arcs, the establishment of the auroral electrojet currents as Hall currents, the irregular nature of the electric fields, and the reversal of the electric fields between the eastward and westward electrojet regions have been some of the important observations. The existence of large fields parallel to $\vec{B}$ is doubtful although small magnitude fields are possible. Recent barium ion cloud observations in the polar cap have indicated that the long assumed electrojet return current across the polar cap does not exist. Convection across the polar cap is anti-sunward. Measurements of D.C. electric fields at lower latitudes are much more sparse. They have shown some agreement and some disagreement with Sq dynamo electric field predictions. Variational effects in the electric fields have been found wherever strong fields exist. Both electrostatic and electromagnetic phenomena have been detected looking at the A.C. components.

I. Introduction

The existence of large scale, electric fields has long been needed for interpretation of many geophysical phenomena. Theories involving a neutral wind driven dynamo to drive the Sq current system were used to explain the diurnal magnetic variation data back at the beginning of the century; (see Chapman and Bartels, 1940). Large scale convection fields in the magnetosphere evolved from the work of Axford and Hines (1961), to tie together magnetospheric and auroral phenomena. Only recently have actual measurements progressed to the point where comparison to theory has become possible. The purpose of this paper is to define the methods now available for measuring electric fields, to consider the results obtained from recent measurements and to relate these measurements to the predicted sources of electric fields where possible. DC electric fields will be the primary subject with short comments on variational and AC electric fields. In order to understand the relationships to theory, a brief outline of the sources of electric fields follows.

A. Magnetospheric electric fields

Energy and momentum from the solar wind is transferred to the magnetosphere by interaction at the boundary of the magnetosphere. Convective motions are set up by the generated large scale electric fields. Since the early paper of Axford and Hines (1961), many authors have looked at convection in both open and closed magnetospheric models. A review by Axford (1969) on convective processes and one by Obayashi and Nishida (1968) on the large scale electric fields are helpful references. The source of the convective electric field depends on the model of the magnetosphere used. In a closed or shielded magnetospheric model the solar wind, as it flows past, exerts frictional forces on the magnetospheric plasma. These result in polarization fields from charge separation (see Piddington,1960; Axford, 1964). In an open configuration of the magnetosphere (Dungey, 1961) the electric field from the bulk motion of the solar wind can penetrate into the magnetosphere.

Regardless of the source of the electric field driving the convection, these fields will propagate down the field lines to the ionosphere. If one assumes the magnetic field lines as equipotentials, then the D.C. electric field is imposed on the ionosphere in accordance with the configuration of the magnetic field. Farley (1959) and Mozer (1970) have made studies on the mapping of the fields observed in the ionosphere out the magnetic field lines. Reid (1965) has studies how magnetospheric fields of various scale lengths map down the field lines into the ionosphere. If a finite conductivity exists along the field line and potential drops occur, then one must return again to Maxwell's equations for a solution. Thus, the ionosphere can influence magnetospherically generated electric fields. It is noted that Hall currents have no loading effect on the magnetospheric field (Farley, 1959, 1960; Reid, 1965).

Convection patterns have been derived by looking at ground magnetic variations and building a model that would create these disturbances. Nishida (1966) has separated effects of the auroral electrojet (DP1) from the more worldwide fluctuations (DP2) and has derived current systems and electric fields producing each. As will be seen in section III, this technique may have pitfalls in that the measured electric fields do not in general directly relate to the magnetic field variations.

Inside the plasmapause co-rotation of the plasma is generally assumed. How far out co-rotation exists is not clear. Depending on the frame of reference of the observer, there exists a small electric field from this motion. One also must remember that fields generated in the ionosphere will propagate up the field lines following the same laws.

B. Ionospheric electric fields

In the auroral and polar regions of the ionosphere the situation is dominated by the magnetospherically generated electric fields described previously. One must also consider localized electrostatic fields.

At lower latitudes the electric field may be dominated by the dynamo field driving the Sq current system. Maeda (1955) used geomagnetic variations and assumed conductivities to derive the electric field. He then derived the dynamo field from the wind patterns and subtracted this from the above to get the resultant electrostatic field. Figure 1 (Figure 5 of Obayashi and Maeda, 1963) shows Maeda's resulting horizontal electrostatic field and the calculated vertical electrostatic field (note that these fields are all perpendicular to $\vec{B}$). One sees the basic current cells from the Sq pattern in the figure with the amplitudes from 1 to 5 mv/m. Matsushita (1969) has made a more recent calculation obtaining similar but slightly different results.

These fields generated in the E region of the ionosphere will propagate up to higher altitudes. The amount of attenuation in the propagation has been studies by Farley (1960, 1961) and Spreiter and Briggs (1961) showing that large scale D.C. fields propagate up the field lines nearly unattenuated while small scale variations will be attenuated according to wavelength and to the geophysical conditions present.

Near the equator where the magnetic field lines become horizontal, the vertical fields are more prominent. Polarization fields driving the electrojet will be in evidence.

II. Measurement techniques

A. Early experimental attempts

The measurement of electric fields has historically lagged behind theory due to the difficulty of measuring the small geoelectric fields that exist. An object immersed in a plasma will assume a potential such that the net current flow between the object and the plasma is zero. The resultant sheath around the object often contains fields several orders of magnitude larger than the ambient fields in the medium. The early attempts at measuring electric fields suffered from trying to look at millivolt per meter fields through volt per centimeter sheath fields.

Imyanitov, et al.(1964), Gdalevich (1963) and Gdalevich, et al. (1965) attempted in the late 1950's and early 1960's to use the field mill technique (successfully used in atmospheric electricity measurements) of measuring the current to a surface alternately screened from the external field by a shutter. Results were obviously sheath fields of the order of volts/cm. Imyanitov et al. estimated the external field to be of the order of 100 mv/m. The use of the field mills has been abandoned until recently, when Knott has attempted to use them to detect the vehicle wake and then estimate the electric field from the configuration of the wake (Knott, 1970; Fahleson, et al., 1970).

A new approach was taken by Kavadas and Johnson (1964). The potential difference between two closely spaced electrodes was measured. Although the interpretation of the data was hindered by the asymmetry of the electrodes and small separation, fields of the right magnitude were detected in the auroral region from Ft. Churchill. A variation of the technique was tried by Unger and Rawer (1967) but suffered from the aforementioned problems.

Subsequent experiments were proposed by Dolezalek (1964) using spherical probes on long booms and by Aggson and Heppner (1964) using long cylindrical antennas. The resulting probe technique, described in II-B, is one of the two direct methods most commonly used for electric field measurements.

The second direct method involves following photographically the motion of clouds of barium ions (Ba^+) injected into the medium, (Föppl, et al., 1965). This method (section II-C) is restricted to twilight conditions as the Ba^+ cloud must be sunlit, and the cloud is dim relative to the sky for solar depression angles of less than 6°.

Several indirect means of deriving electric fields will be discussed in section II-D.

B. Double floating probe method

The double floating probe technique, as defined by Aggson and Heppner (1964) and by Dolezalek (1964) and reviewed by Fahleson (1967), depend on deploying symmetrical sensors, whether cylindrical or spherical, some distance away from the vehicle. As shown by Langmuir and Mott-Smith (1926), a probe in a plasma will seek a potential that will establish a current balance between the probe and the plasma. If no current is drawn from the probe, then the potential will depend on the properties of the medium, including potential differences existing in the medium. The technique as shown schematically in Figure 2 is to measure the floating potential of each sensor with respect to the vehicle potential and differentially substract the resultants, eliminating the vehicle potential. If no electric field exists, the probes will float at the same potential. The result may be expressed by

$$(V_A - V_S) - (V_B - V_S) = V_A - V_B = (\vec{E} + \vec{v} \times \vec{B}) \cdot \vec{d} \qquad (1)$$

where $\vec{E}$ is the electric field in the rest frame,

$\vec{v}$ is the velocity of the probe system,

$\vec{B}$ is the earth's magnetic field,

$\vec{d}$ is the vector separation of the sensor midpoints,

V_A, V_B, V_S the potentials of the sensors (A and B) and vehicle or spacecraft(S).

The method is subject to many potential hazards; hence care must be taken in using the technique. Fahleson (1967) and Aggson and Heppner (1964) have discussed in detail the various pitfalls which will only be summarized here.

The most obvious problem (see equation 1) is that of Lorentz invarience. Since E is often small by comparison to $\vec{v} \times \vec{B}$ (especially true for low latitude ionospheric measurements), the accuracy to which $\vec{v} \times \vec{B}$ is known both in magnitude and direction is a limitation on the accuracy of the measurement of $\vec{E}$. For instance a polar orbiting satellite moving at 8km/sec perpendicular to the earth's magnetic field of 0.5 gauss will generate a 400 mv/m $\vec{v} \times \vec{B}$ field. In practice this large field limits the detection of small ambient fields in the direction of maximum $\vec{v} \times \vec{B}$.

Many potential pitfalls can be eliminated by symmetry, both in shape and material. The current balance depends on photo emission as well as the collection of ions and electrons and the current drawn by the voltmeter. Thus, any shadowing of the sensors that is not symmetrical will cause a change in the floating potential. Symmetry will allow contact potential errors to be cancelled through the differential subtraction. Variations in work functions over the material can cause asymmetric photoemission effects, thus a stable and relatively uniform work function is desired.

The input impedance to the electronics must be high so that the current drawn by the electronics will not modify the floating potential by loading the plasma. The plasma impedance varies from 10 to 100 kΩ in the lower ionosphere to greater than 10 megohms in the magnetosphere.

Two of the hardest effects to characterize are sheath overlap and wake effects. Both of these can be minimized by moving the sensors well away from the vehicle. In the case of cylindrical antennas this is done by insulating the innerportion of the rod while for spheres the supporting boom is insulated. These problems are most critical in the distant magnetosphere at middle and high latitudes where the low plasma density results in Debye lengths of meters.

Most of the effects mentioned produce errors that are of the order of kT, where k is the Boltzman constant and T is the plasma temperature, thus, the error analysis for a magnetospheric experiment is much more critical than in the ionosphere.

Increasing the length of the baseline not only helps in minimizing errors, but also increases the sensitivity of the experiment. It can, however, reduce the frequency response to short wavelength A.C. signals. Equation 1 is true for A.C. signals only as long as the wavelength is long compared to $\vec{d}$. For electrostatic waves having wave lengths of the order or greater than the Debye length the potential difference must be divided by the wavelength ($\lambda << |\vec{d}|$). Spheres as opposed to cylindrical antennas have a simpler geometry and effectively make the measurement at a point. The use of cylindrical antennas effectively integrate effects over the length of the probe. The cylindrical antennas are easier to extend to large distances resulting in a larger $\vec{d}$ and more signal. The greater distance also lessens the wake and shadowing problems.

The first flights using this technique were made by Aggson et al., (1967) in 1966 using cylindrical antennas and by Mozer and Bruston (1967) in 1966 using spheres. The flight by Aggson et al., was made at middle latitudes at a time when the Sq field was very weak. The trajectory was such that $\vec{v} \times \vec{B}$ was large. The vector sum of all three components matched $\vec{v} \times \vec{B}$ to within a millivolt per meter demonstrating the technique (see Aggson, 1969). Also, an analysis of whistler results from this flight agrees with Appleton-Hartree theory (Maynard et al., 1970). The technique is applicable to both ionospheric and magnetospheric measurements with the above limitations. An extension of this technique has been used at balloon altitudes by Mozer and Serlin (1969) and Mozer and Manka (1971) allowing continuous measurements over long time periods, (see Section III-B).

C. Barium release experiments

While the probe technique can provide good spatial coverage (in altitude from rockets and over all latitudes and longitudes from satellites) studies of variations in time (excluding the balloon flights) are limited. The barium release experiments provide a means for looking at temporal variation in regions of low electric field strength (in conditions with high electric fields the clouds move more rapidly combining spatial with temporal variations). Beginning from the study of comet tails, the idea of using an artificial ion cloud as a probe for the study of ionospheric and magnetospheric electric fields was developed by the group at Max-Planck-Institute (see Föppl et al., 1965). The technique has provided much useful D.C. electric field data in the ionosphere and more recently in the magnetosphere.

Barium makes an ideal ion source in that the resonance lines are in the visible spectrum and the photoionization efficiencies are high. The barium is evaporated into the medium in the thermite reaction involving Ba and CuO with an excess of barium (Föppl et al., 1967) producing neutral and ion clouds. A small percentage of strontium is usually present. In the initial phase the vapor expands rapidly until it reaches equilibrium with the ambient medium. Diffusion governs further expansion of the neutral cloud. A cigar shaped ion cloud is formed, aligned with the earth's magnetic field and moves under the influence of the electric field and, if the cloud is at low altitudes, neutral winds, while the neutral cloud moves with the winds. Figure 3 shows a typical neutral cloud with two well-developed ion clouds from two other releases. The ionization process involves resonance absorption resulting in spontaneous transitions to a metastable state and then photo-ionization from the metastable state (Haerendel and Lüst, 1969).

The electric field seen by the cloud is derived from the motion of the cloud. The clouds are tracked optically from two or more sites and their position is triangulated with time using the star patterns on the film. The component of the field perpendicular to the magnetic field is found from the transverse velocity of the cloud, (Haerendel et al., 1967).

$$E_\perp = \left(\frac{1+\lambda^*}{2}\right) \frac{B}{C} \left[\left(\frac{\vec{B}}{B} \times \vec{u}_\perp\right) + \frac{1}{R}\left(\vec{u}_\perp - \vec{u}_{n_\perp}\right) + \frac{\lambda^* - 1}{\lambda^* + 1}\left(\vec{u}_n \times \frac{\vec{B}}{B}\right)\right] \qquad (2)$$

where λ^* is the ratio of the integrated Pedersen conductivities along the field lines intersecting the cloud to those outside.

$u_{n_\perp}$ is the transverse neutral wind velocity

$u_\perp$ is the transverse ion cloud velocity

R_i is the ratio of the gyro frequency to the ion neutral collision frequency.

The effects of the second term may be kept small by keeping the release at altitudes where the collision frequency is small compared with the gyro frequency. This condition holds above 190 to 200 km, thus in general, limiting the technique to higher altitudes. The effects of the third term are controlle by the size of the release and the local conductivity. Various sizes of releases from a fraction of a kilogram up through 50 kg have been tried. The larger releases have caused a significant perturbation of the medium requiring a consideration of the third term (i.e. a 24 kg. release from Ft. Churchill resulted in a λ^* of 1.5) (Haerendel et al., 1969). A 2 or 3 kg. release produces good observable clouds without a significant effect on the medium (see Wescott et al., 1969; Haerendel and Lüst, 1969). With Ri >>1 and $\lambda^* \approx 1$, equation 2 reduces to

$$E_\perp = \frac{1}{C} (\vec{B} \times \vec{u}_\perp) \tag{3}$$

The barium cloud technique was first used at mid-latitudes in small fields and later applied in the equatorial, auroral and polar cap regions. At middle and low latitudes, the twilight requirement provides a severe restriction on local time coverage; however, in the auroral and polar cap regions the time of the year can be varied so as to include most of the local magnetic time conditions. The technique has also been applied to the magnetosphere with a release from the HEOS satellite. Here the cloud acceleration to the ambient plasma velocity must also be taken into consideration (Haerendel and Lüst, 1970).

D. Indirect measurement techniques

Indirect measurements in general fall into two categories. The first involves measuring drift velocities while the second involves drawing conclusions from particle pitch angle and energy spectra.

Drift motions have been detected in two ways. The first of these was by Carpenter and Stone (1967) who interpreted changes in whistler dispersion as being caused by the motion of field aligned ducts. They detected a westward field of 0.3 mv/m lasting for over an hour at L = 4.5 28 minutes before the onset of a bay at L = 7. Note that since this technique is sensitive only to inward velocities, only estimates of east-west fields may be obtained. A variation on this technique proposed by Troitskaya et al., (1968) looks at the drift velocities of micropulsations.

The second technique utilizing drift motions has been the observation of nighttime equatorial electrojet irregularity motions using VHF backscatter radar (Balsley, 1969). The technique is good for velocities between 50 and 360 m/sec., and the velocity is related to the east-west electric field by

$$\vec{E}y \simeq - 0.88 \times 10^{-6} \vec{u}_{ey} \text{ volts/m.} \tag{4}$$

Significant findings include the reversal of the field at 0630 hours and 2030 hours local time and an increase in velocity just prior to the reversal.

Alfvén and Fälthammar (1963) have proposed that a different pitch angle distribution will exist for electrons and protons if a parallel electric field exists along the field line. Thus, for zero electric field the ratio of the parallel to perpendicular energies of the electrons must be equiqalent to that of the ions. They show that

$$E_{\parallel} = -K \frac{dB}{ds} \tag{5}$$

where

$$K = \frac{Wi_{\parallel} \; We_{\perp} - We_{\parallel} \; Wi_{\perp}}{|e| B \; (Wi_{\parallel} + We_{\parallel})} \tag{6}$$

s is the path along $\vec{B}$

W is the energy of the various particles denoted by the subscripts i, e, $\perp$, and $\parallel$ referring to electrons, protons, perpendicular and parallel.

Thus, the energy ratios can differ only in a homogeneous magnetic field (where $\frac{dB}{ds} = 0$).

Van Allen (1970) has drawn conclusions on the electric field in the tail from observations of solar electrons of energies greater than 50 kev. by two different satellites. By establishing that the solar electron flux in the tail as observed by Explorer 35 in orbit about the moon was identical to that outside the magnetosphere, he concludes that the $|\int \vec{E} \cdot d\vec{s}|$ from a point outside the magnetosphere into the tail must be less than 1.5 kv. He points out that this does not limit the existence of higher fields in a point by point sense, but argues toward the existence of an open tail.

III. Electric field measurements and interpretation

A. Low and middle latitudes

Due to the small magnitude of the fields at low and middle latitudes, few measurements have been made. Since one is in general looking for one or two millivolts per meter, the desired field is near the accuracy of probe measurements, especially when $\vec{v} \times \vec{B}$ may be as large as 50 to 100 mv/m. As previously noted in II-B Aggson et al., (1967) chose a trajectory with a large $\vec{v} \times \vec{B}$ to check the technique. The early measurements by the Max-Planck group with barium clouds were in the Sahara desert (Haerendel et al., 1967; Haerendel and Lüst, 1968). Rieger (1970) has taken these measurements and added to them more recent equatorial and mid-latitude release data.

The releases reported by Rieger (1970) cover magnetic latitudes 53°, 36°, 26°, 0° and -43°. The fields obtained varied from 0.3 to 4.0 mv/m. All of the measurements were by necessity in the twilight regions on the edge of the dynamo current cells as seen in Chapman and Bartels, (1940). Rieger compared his directions with those from theoretical calculations of Maeda (1955) and Matsushita (1969) and found better agreement with Maeda's calculations. Note that the assumption was made from Speiter and Briggs' (1961) calculations that the dynamo field at 110 km would be communicated up the field line without appreciable attenuation to the altitudes of the Ba^+ clouds (150 to 300 km).

Measurements with Ba^+ at the equator present a different problem in that F region field lines terminate outside the electrojet. The perpendicular components there are east-west and vertical. Rieger's measurements showed an eastward field in the evening (~1800 hrs local) and a westward field

(~05:30 hrs. local) in the morning with values of .45 to 2.6 mv/m. Balsley (1969) has shown the reversal in the east-west field from drift motion measurements to be a few hours after sunset (section II-D) and in directional agreement with Rieger's results. It is noted that the vertical fields (upward, evening; downward, morning), corresponding to a "north-south" field if propagated down the field line, were larger than the horizontal.

Rieger's conclusion is that strong evidence exists for dynamo generated fields at evening twilight at mid-latitudes. At the equator he concludes the current is from polarization fields.

Moving up to latitudes corresponding to the plasmapause, Gurnett (1970) and Cauffman and Gurnett (1971), using INJUN-5 double probe data, impedance data and electron density data, have been able to define the plasmapause unambiguously on eight occasions on the night side. On five of these, they have noted a 10 to 20 mv/m change in the electric field and conclude that it indicates a change in the plasma convection at the plasmapause. It is noted that these fields are at the limit of resolution of the experiment and are seen only part of the time on the night side; hence, the general case is still ambiguous. It is evident that the plasmapause is not in general the boundary for strong convection as proposed by Brice (1967) but this region exists nearer the auroral shells (Heppner, 1969).

B. Auroral regions

Many measurements have been made in the auroral regions with both the double probe and barium ion cloud techniques. The results show good agreement on some points and disagreement on others. The subject of electric fields parallel to $\vec{B}$ has resulted in much controversy and will be looked at in section III-D. The measurement of perpendicular electric fields has resulted in much insight into convective patterns.

No attempt will be made to draw an overall convection pattern as analyzed data is still somewhat sparce. General comments will be injected where appropriate. Some general conclusions can be made about auroral fields from the available data; these are summarized in Table 1 with reference to concurring and dissenting views. Basically both double probe and ion cloud measurements have generally agreed that the magnitude of the field varies from near or less than 10 mv/m to over 130 mv/m., the typical values being in the 30 to 50 mv. range, and that the magnitude and direction is very variable over short distances and time. Where directional information has been obtained, the field has been predominently southward (northern hemisphere) during negative bays and northward during positive bays. The relative magnitude of the east-west component has in general been small for the barium measurements while Mozer and Fahleson (1970) have found stronger east-west components using the probe technique. The nature of the bay activity from the magnetograms and the measured electric field prescribes that the currents causing the magnetic perturbations are Hall currents. A composite of Ba^+ cloud results plotted in magnetic latitude and magnetic local time is shown in Figure 4 (polar cap results from Heppner et al. (1971a) have been added to Figure 2 of Haerendel and Lüst (1970)). The general features of eastward and westward flow, respectively, in the morning and evening auroral belt and the anti-solar flow across the polar cap are evident. More recent (unpublished) data from a large number of flights provide additional confirmation of the general features.

The large variability in magnitude, both spatial and temporal, limits direct comparisons with ground magnetogram data primarily to vector directions. Figure 5, taken from the Ba^+ work of Wescott, et al., (1969) is illustrative of the variability in magnitude. Obviously the point to point conductivity must be known to calculate electric fields. Thus, attempts to derive electric field configurations from ground data (e.g. Bullen, 1968) can at best produce qualitative results about gross convection patterns.

An important question is what happens to the field inside an auroral form. Aggson (1969) deduced from double probe experiments that the field in an arc was greatly reduced. From that he eliminated the Swift (1963) dynamo model of the electrojet and two models of Bostrom (1967) involving field aligned currents, both requiring equal or greater fields within the arc. The resultant picture, similar to that of Piddington (1964), was one of the ionosphere Pederson conductivity loading the magnetospheric dynamo. Thus, the magnetosphere was considered as a current source. The observational evidence was added to by Wescott et al., (1969, 1970) and Potter and Cahill (1969). Recently, however, Mozer and Fahleson (1970) have published data which contradict this, conluding that the field remains constant or increases crossing the boundary of an arc. Thus, at least in specific cases, the results are still controversial.

An interesting region has been the transition from positive to negative bays. Several Ba^+ releases have seen field reversals in this region. In the third flight of Wescott et al., (1969) the initial cloud moved westward in response to the positive bay. However, the other clouds, released more to the north, reversed direction several times coincident with changes in magnetic activity (see W3.3 in Figure 4). These were apparently in the region between positive and negative bay activity (see model by Heppner (1967) showing overlapping positive and negative bay regions). Similar reversals occur on the pole side of the auroral region. Haerendel et al., (1969) observed a reversal on a flight from Ft. Churchill in which the aurora was located to the south (launched at 02 hrs. local time). Cauffman and Gurnett (1971) using a double probe on INJUN-5 have seen reversals of the field on polar cap side of the auroral zone. Their basic pattern is for sunward convection on the low latitude side and anti-sunward convection on the high latitude side. Double probe data from OGO-6 shows this reversal to be a typical characteristic but with the magnitude and the space over which it occurs quite variable (see section III-D, also).

Perturbations of the field in one hemisphere should also occur in the other hemisphere at the conjugate point. Auroral conjugacy has been established by Belon et al., (1969) with simultaneous airplane flights in conjugate locations using all-sky cameras and image orthicon TV systems. During some orbits, a polar orbiting satellite will pass through regions which are approximately conjugate. Gurnett (1970) has found good correlations between hemispheres on a large scale oscillatory structure. It must be noted that for this interpretation to be made the structure must be relatively stable over the time scale of the satellite traversal from one pole to the other. Looking at small scale irregularities, Maynard and Heppner (1970) found conjugate agreement in the point of onset of the irregularities. More will be said on variational fields in section III-E.

The balloon measurements of Mozer and Serlin (1969) and Mozer and Manka (1971) have utilized the double probe technique at balloon altitudes to attempt to measure ionospheric and magnetospheric electric fields. They claim that the results represent several hundred kilometer averages of the horizontal ionospheric electric field. Results, especially those of Mozer and Manka (1971), have tended to reproduce the gross features as seen by _in situ_ measurements including lower fields near plasmapause latitudes, the reversal near polar cap regions and the basic gross time dependence of the north-south component. However, several problems exist. The magnitude of their east-west component is quite often a large fraction of, or greater than, the north-south component, which is generally not the case in the *in situ* measurements. Most of the aforementioned Ba^+ experiments have measured much larger north-south electric fields than east-west fields. One must remember that atmospheric fields are large and variable and mainly vertical. A small atmospheric variation could be equivalent to the measured result. Measurements over a wide latitude range on a given day are necessarily made under greatly differing atmospheric conditions.

C. The question of parallel fields

The existence of electric fields parallel to $\vec{B}$ in the auroral zone has long been a source of controversy. As seen from Table 1, it is this point that has evoked the most disagreement. Parallel fields have been sought by theorists as a convenient means of auroral particle acceleration (see Alfvén and Falthammer, 1963; Persson, 1966, 1967).

Mozer and Bruston (1967) and later Mozer and Fahleson (1970) have taken probe measurements from a flight that had a large precession cone and have deduced that a parallel field of 20 mv/m existed over the first part of the flight. The method requires the assumption of a constant field along $\vec{B}$ for a period longer than a precession period. The highly variable nature of the fields as observed by other experiments makes this assumption questionable. It was noted by Mozer and Fahleson (1970) that a parallel electric field strength of 20 mv/m would require that the conductivity along $\vec{B}$ be reduced by four orders magnitude, suggesting wave particle interactions as the mechanism (Coroniti, 1968). Mozer and Fahleson show a perpendicular field increasing with altitude during the period where they deduce the parallel field. This is necessary to maintain a curl-free electric field in the steady state condition. By comparison, Potter (1970) sees no systematic variation with altitude of the perpendicular field and deduces that no parallel fields of significant magnitude existed. Also, multiple releases of Ba^+ clouds over the 200-300 km altitude range have not indicated any systematic changes in E as a function of altitude.

Mende (1968) looked at the density distribution of Ba^+ clouds. Considering gravity and polarization of the cloud, he concluded, from the absence of any field aligned cloud distortion, that the field along B in the ionosphere must be less than 60 μv/m: (the field within the cloud being up to 10 times less, or 6 μv/m). However, Mende neglected ambipolar diffusion. Scholer and Haerendel (1971) have recently repeated the calculations taking into account ambipolar diffusion and have reached a similar conclusion to Mende. Föppl et al., (1968) and Wescott et al., (1969) both reported that no unusual vertical distortion of the clouds have been observed and thus conclude that parallel electric fields are several orders of magnitude less than the perpendicular fields. Mozer, in a discussion led by Falthammer (1969), argued that the possibility of anomalous resistivity in a turbulent plasma could affect the results.

If an auroral form acts as a load on the convection field, as discussed earlier, then a parallel field may exist at higher altitudes or the convection pattern in the magnetosphere may be very irregular. If a parallel electric field does exist then the magnitude may be very small as the drop can be spread out over the entire magnetic field line. Hulqvist reported at this meeting of parallel fields derived from differences in pitch angle measurements (see section II-D), which would be small in magnitude if spread out along the field line. Cauffman and Gurnett (1971) have attempted to deduce a small parallel field from the differences in variations in the field between INJUN-5 apogee and perigee data (note that the measurements were of necessity made at different times).

It would appear that the evidence is weighed toward small or nonexistent steady state fields along $\vec{B}$. This does not preclude electrostatic waves and short duration parallel electric fields.

D. Polar cap measurements

The question of where the return current from the auroral electrojet flows led people to postulate a constant ionospheric Hall current across the polar cap consistant with the magnetic variations observed on the ground. One would thus expect an electric field in the direction of $\Delta\vec{H}$ (the change in the horizontal component of $\vec{B}$) or, if the Pederson conductivity is large, an electric field vector displaced from $\Delta\vec{H}$ in the direction of the current.

Wescott et al., (1970) and Heppner et al., (1971 a, b) found using Ba^+ cloud data from three flights (12 releases) in the polar cap that the convection velocity was away from the sun resulting in an electric field pointing toward the evening sector. The direction of the electric field forbade the explanation of the total ground magnetic variations in turns of Hall or Pederson currents. The same type of discrepancy showed up in the Ba^+ release from HEOS in the magnetospheric tail at 12.5 Re, 42° mag., lat., by Haerendel and Lüst, (1970).

The polar cap field, at locations 6 to 10° from the northernmost aurora, was found by Heppner et al., (1971 a, b) to be more uniform in space and time than the auroral zone electric fields. Small scale changes were still very evident. The magnitudes were in the range of 20 to 40 mv/m. No significant differences were detected between the dawn and dusk magnitudes. The paths of the clouds from flights 1 and 2 have been plotted in Figure 4 for directional comparisons to the auroral zone measurements. Note that the general pattern of electric field reversal previously mentioned in section III-B is followed by the cloud paths. The electric field vectors were directed from

40 to 80° from the earth sun line at 2-3 hours magnetic local time and 80 to 120° at 17-18 hours magnetic local time.

Satellite data from OGO-6 has shown a generally stable field across the polar cap of 10 to 40 mv/m with the same basic orientation as seen with barium releases. The exception to this is in the morning side cusp region which Axford and Hines (1961) called the "zone of confusion". An example of a polar pass is shown in Figure 6 showing the field reversals on the poleward side of the auroral zone and the uniform polar cap field. It must be remembered that since only one component is measured, the total horizontal field is still undetermined. However, OGO-6 was oriented such that it always measured the component perpendicular to the earth-sun line which from the Ba^+ releases should be the major component.

Different results are obtained by Cauffman and Gurnett (1971) and Frank and Gurnett (1971) who state that the general polar cap field is small and that polar cap convection exists mainly near the auroral zone. In weighing these results one must remember the high threshold value for the INJUN-5 data and the possible ambiguities in $\vec{v} \times \vec{B}$ and direction (affecting the vector subtraction). It is noted that both moderately strong and near zero fields have been seen by both experiments, the question being that of the general case. The Ba^+ data supports the OGO-6 results.

The fact that the polar cap field is in the wrong direction for an ionospheric return current interpretation led Heppner et al., (1971 a, b) to postulate that little or no current exists and that the magnetic deflection over the polar cap is from two regions of net field aligned current completing the electrojet circuit. Figure 7 shows their general ionospheric pattern of current flow and the regions of net field aligned current flow, an inward current in the morning sector and an outward current in the region between the positive and negative bay electrojets. The closure of the system is in the magnetospheric equatorial plane consistant with observed asymmetric ring current effects.

E. Variational effects and A.C. electric fields

One of the most striking features in all Ba^+ cloud measurements has been the striations of the ion clouds (see Figure 3). They have been observed in large and small releases and at mid latitudes (developing at a much slower rate) as well as in the auroral and polar cap regions. In the auroral regions it is often hard to visually distinguish them from rayed aurora. Many studies have been done attributing the origin of the striations to instabilities, the favorite being the $\vec{E} \times \vec{B}$ instability (see Simon, 1963). More important to the physics of the ionosphere is the question of whether the Ba^+ ions cause the instability or whether they merely trace out a pattern of variations that commonly exists. Wescott et al., (1969) believe the latter to be the case for the smaller releases normally used for geophysical experiments.

Evidence of a highly variable spatial structure of the fields is seen in a gross scale in the satellite results of Cauffman and Gurnett (1971) (defined as high latitude noise) and of OGO-6. On a finer scale, Maynard and Heppner (1970) found that small scale irregularities exist wherever large convective electric fields exist. This variational structure, resulting in an AC signal of less than 50 Hz, reported by Maynard and Heppner (1970) from OGO-6 and OV1-10 data and by Heppner (1969) from OV1-10 data, was found to basically follow the variations of the auroral zone with Kp. These fields were also in general present over much of the polar cap. Recently Holtet et al., (1971) have found noise bursts from near D.C. up to 1.5 kHz in the 100 to 120 km region on a flight into an auroral glow.

Although A.C. fields will not be treated in detail here, mention should be made of a few general results. ELF and VLF electric fields have in many cases confirmed and added to results obtained previously looking at the magnetic component of electromagnetic waves (e.g. the work of Gurnett and co-workers). A significant new tool is the measurement of the Poynting vector by Mosier and Gurnett (1969) and Mosier (1971) which has helped define the source location of several VLF phenomena. Electric field experiments have also led to the detection of electrostatic waves and their effects (e.g. Scarf et al., 1968).

Acknowledgements

The OGO-6 D.C. electric field conclusions given here were part of a paper presented at the Spring AGU Meeting, Washington, D.C., April 1971, by J. P. Heppner, T. L. Aggson and the author were also experimenters. A comprehensive paper on these results will be published elsewhere.

The author wishes to thank Dr. Heppner for helpful discussions during the assembly of this material.

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Table I: Conclusions from Auroral Zone Measurements

	Conclusion	Concurring Views	Dissenting Views
1.	General electric field magnitude of from 10 mv/m up to over 130 mv/m	All	
2.	The field magnitude is very variable over short distances and time	All	
3.	Both the eastward and westward electrojets are Hall currents	Wescott, et al., 1970 Wescott, et al., 1969 Haerendel and Lüst, 1970 Potter, 1970	
4.	The field in an auroral form is reduced in magnitude	Aggson, 1969 Wescott, et al., 1970 Potter and Cahill, 1969 Wescott, et al., 1969	Mozer and Fahleson, 1970
5.	E cannot be simply related to ΔB	Wescott, et al., 1970 Wescott, et al., 1969 Haerendel, et al., 1969 Haerendel and Lüst, 1970	
6.	No systematic variations of amplitude with altitude	Potter, 1970	Mozer and Fahleson, 1970
7.	Parallel fields are in general orders of magnitude less than perpendicular fields	Mende, 1967 Föppl, et al., 1967 Wescott, et al., 1970 Potter, 1970	Mozer and Bruston, 1967 Mozer and Fahleson, 1970 Cauffman and Gurnett, 1971 (?)
8.	Field reversal in direction on the pole side of the auroral electrojets	Wescott, et al., 1969 (pos. to neg.bay) Cauffman and Gurnett, 1971 Haerendel, et al., 1969	
9.	Conjugacy of variational effects	Gurnett, 1970 Maynard and Heppner, 1970	

FIGURE CAPTIONS

Figure 1: Global distribution of the electrostatic field from Sq dynamo considerations from Figure 5 of Obayashi and Maeda (1965) following the work of H. Maeda (1955).

Figure 2: Schematic representation of the double probe technique for measuring electric fields. The vector $\vec{d}$ represents the distance between the element midpoints whether the sensors are spherical or cylindrical.

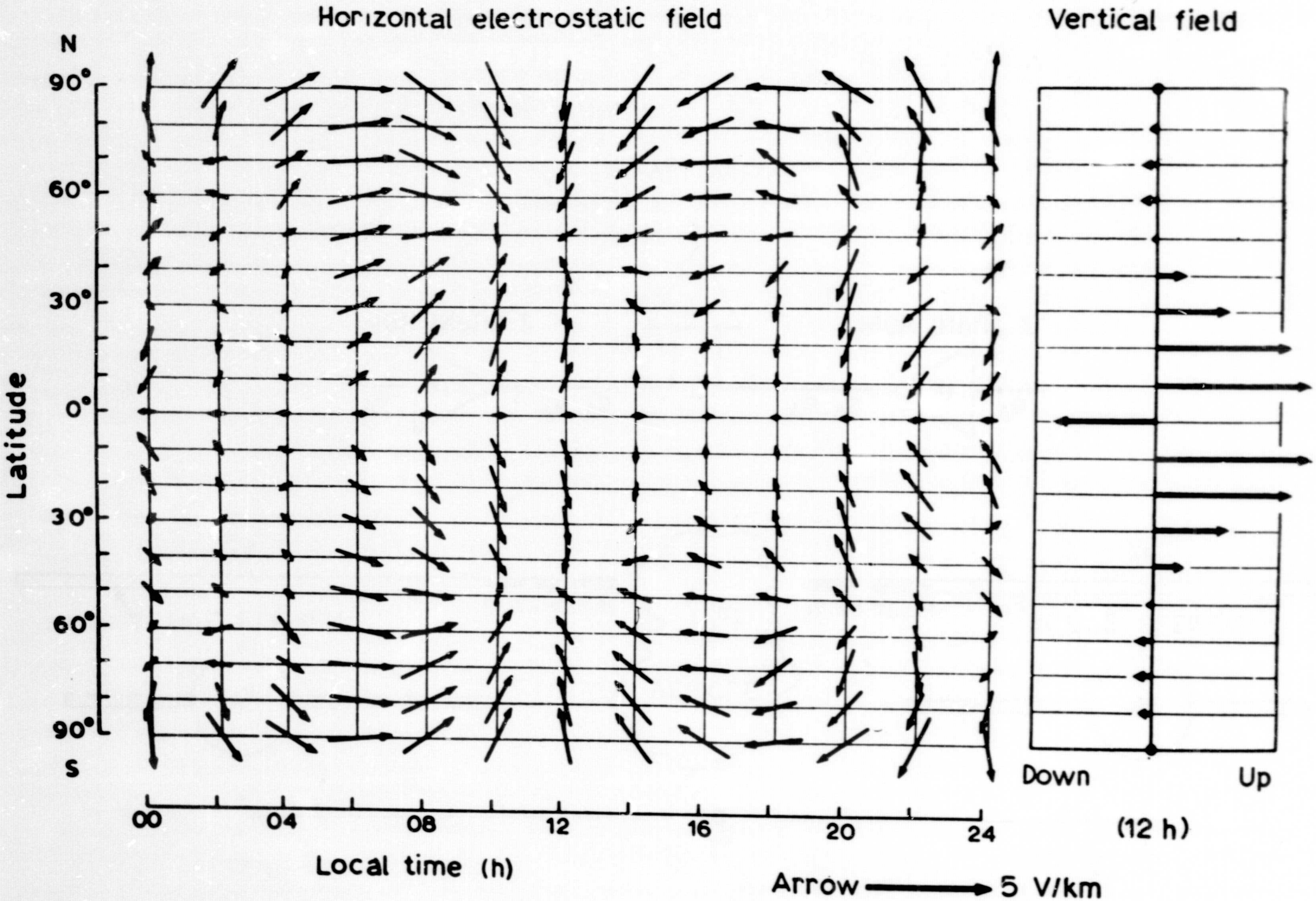
Figure 3: A photograph of a barium release showing a neutral cloud on the left and two cigar shaped ion clouds on the right. Note the field aligned striations of the ion clouds.

Figure 4: A magnetic latitude-magnetic local time plot of the paths of many Ba^+ clouds, (after Haerendel and Lüst, 1970). The numbers preceded by W refer to Wescott et al., (1960), those by H refer to Heppner et al., (1971a) and the others the work of the Max-Planck group (see above reference).

Figure 5: The electric field magnitude perpendicular to $\vec{B}$ derived from four ion cloud motions (Figure 3 from Wescott et al., 1969).

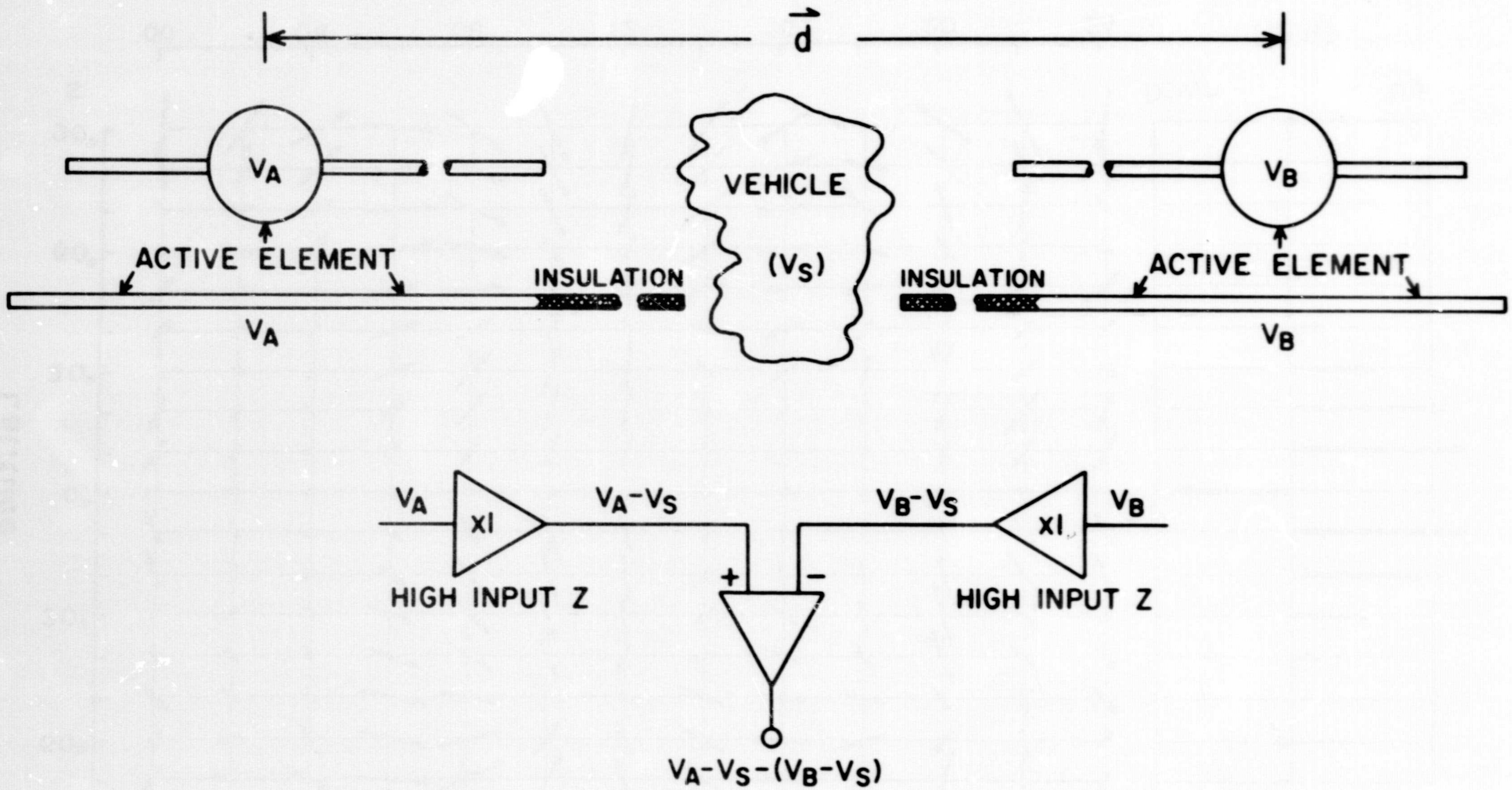
Figure 6: The magnitude of the horizontal electric field perpendicular to the earth sun line for an orbit of OGO-6 after subtraction of $\vec{v} \times \vec{B}$. The northern hemisphere pass went nearly over the magnetic pole. It is believed that the southern hemisphere curve should be shifted upward by 5 to 10 mv/m from a systematic trajectory error in the $\vec{v} \times \vec{B}$ subtraction.

Figure 7: Illustration of the distribution of Hall current electrojets terminated by field aligned currents and the region of net field aligned currents used by Heppner et al. to explain the polar cap data (Figure 14 of Heppner et al., 1971a).



Horizontal electrostatic field
Vertical field
N
90°
60°
30°
0°
30°
60°
90°
S
Latitude
00
04
08
12
16
20
24
Local time (h)
Down
Up
(12 h)
Arrow 5 V/km

FIGURE 1



$\vec{d}$
V_A
V_B
VEHICLE
(V_S)
ACTIVE ELEMENT
ACTIVE ELEMENT
INSULATION
INSULATION
V_A
V_B
V_A
X1
$V_A - V_S$
HIGH INPUT Z
$V_B - V_S$
X1
V_B
HIGH INPUT Z
+
−
$V_A - V_S - (V_B - V_S)$

FIGURE 2

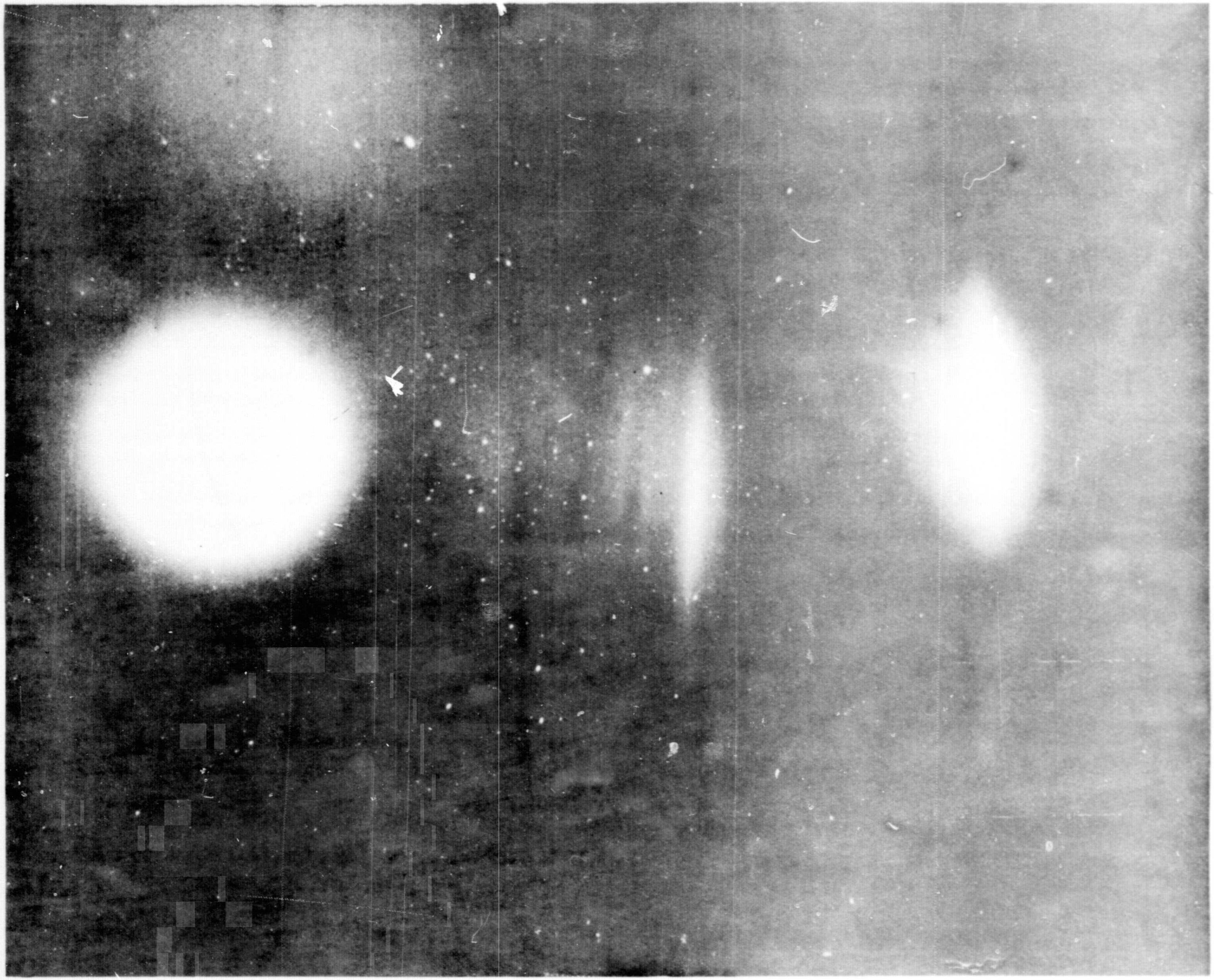


FIGURE 3

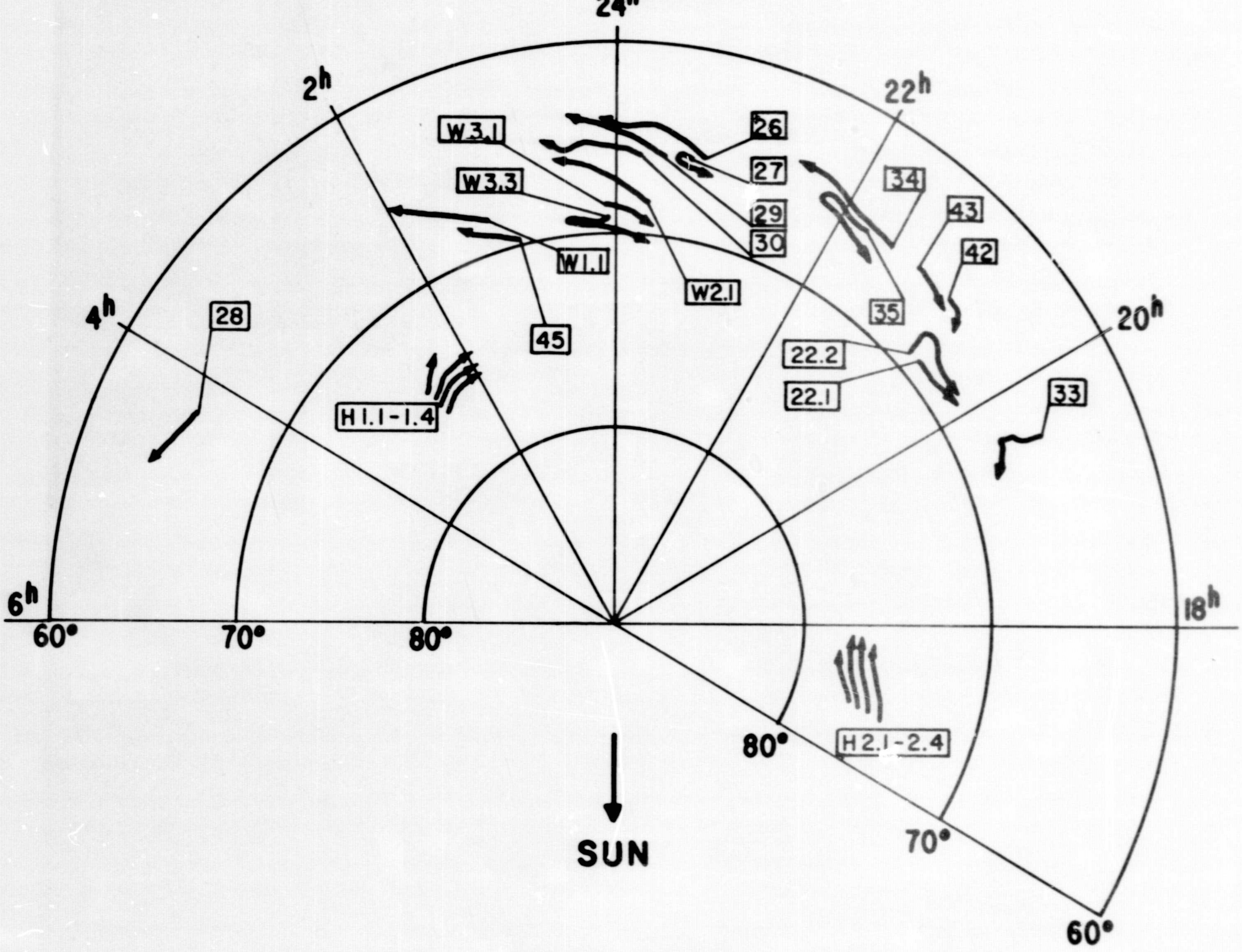

24h
2h
22h
4h
20h
6h
18h
60°
70°
80°
W3.1
W3.3
W1.1
W2.1
45
26
27
29
30
34
35
43
42
22.2
22.1
33
28
H1.1-1.4
H2.1-2.4
SUN

FIGURE 4

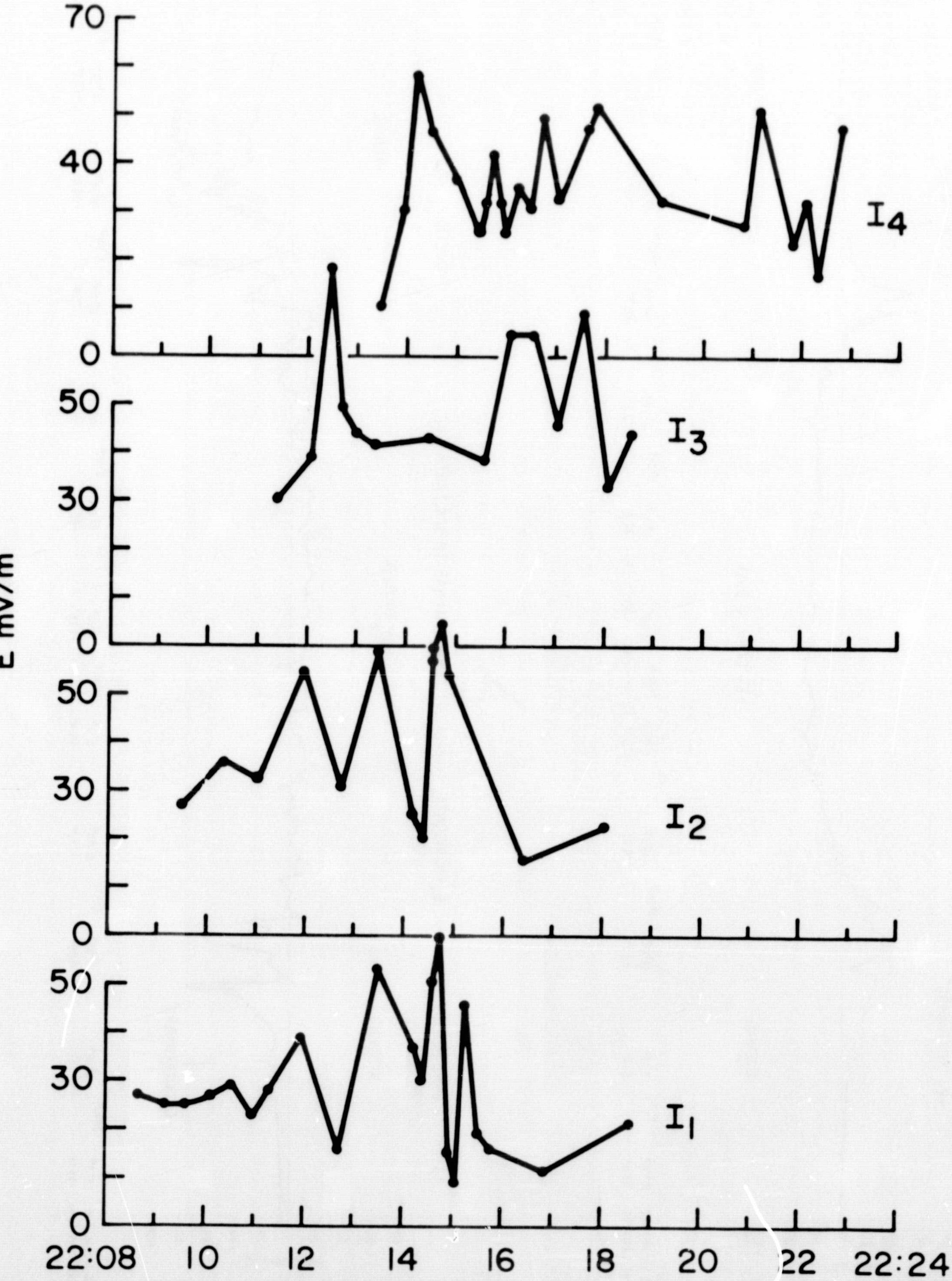

70
40
0
50
30
0
50
30
0
50
30
0
E mV/m
I4
I3
I2
I1
22:08
10
12
14
16
18
20
22
22:24
UT, AUGUST 31, 1967

FIGURE 5

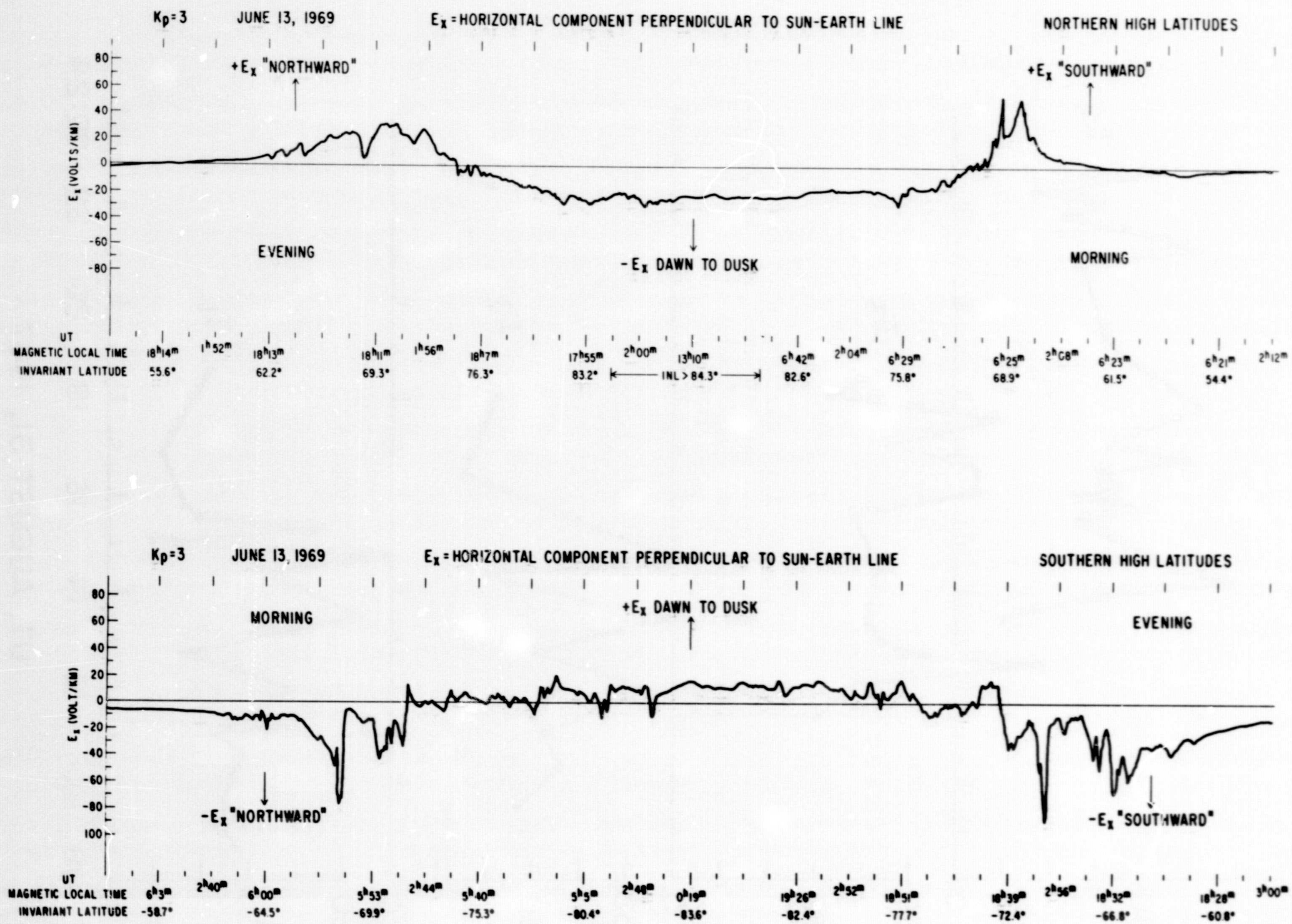
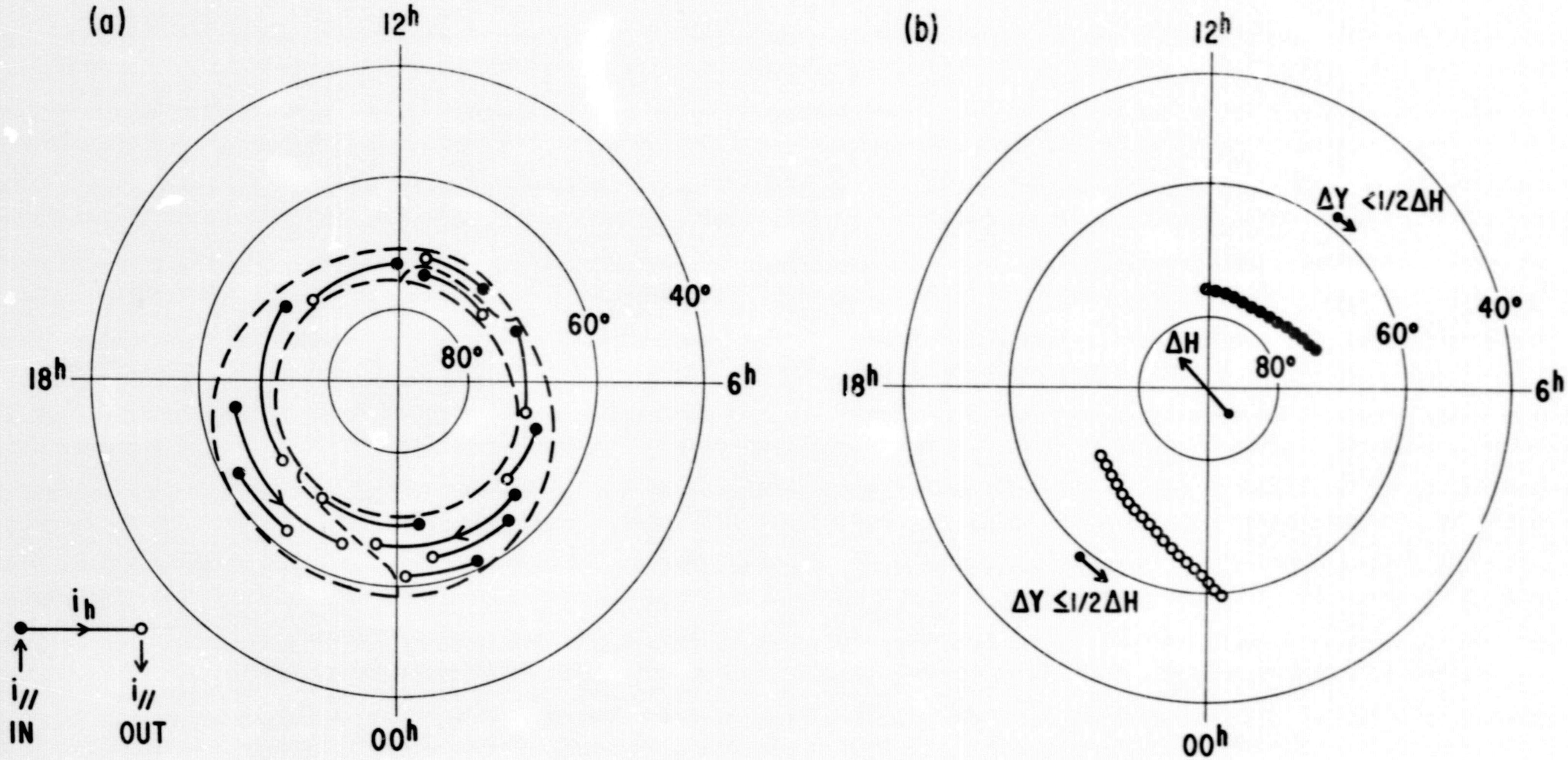

Kp=3
JUNE 13, 1969
E_x = HORIZONTAL COMPONENT PERPENDICULAR TO SUN-EARTH LINE
NORTHERN HIGH LATITUDES
$+E_x$ "NORTHWARD"
$+E_x$ "SOUTHWARD"
E_x (VOLTS/KM)
EVENING
$-E_x$ DAWN TO DUSK
MORNING
UT
MAGNETIC LOCAL TIME
INVARIANT LATITUDE
INL > 84.3°
Kp=3
JUNE 13, 1969
E_x = HORIZONTAL COMPONENT PERPENDICULAR TO SUN-EARTH LINE
SOUTHERN HIGH LATITUDES
MORNING
$+E_x$ DAWN TO DUSK
EVENING
E_x (VOLT/KM)
$-E_x$ "NORTHWARD"
$-E_x$ "SOUTHWARD"
UT
MAGNETIC LOCAL TIME
INVARIANT LATITUDE

FIGURE 6



HALL CURRENT ELECTROJETS
CURRENTS ALONG $\underset{\sim}{B}$ (NOT SHOWN)

AVERAGE IONOSPHERIC INTERCEPTS
OF
EQUIVALENT $i_{//}$ SHEETS

FIGURE 7