TRITA-EPP-89-06

ELECTRIC FIELDS IN THE MAGNETOSPHERE

Carl-Gunne Fälthammar

TRITA-EPP-89-06 .

ELECTRIC FIELDS IN THE MAGNETOSPHERE

Carl-Gunne Fälthammar

December 1989

Invited paper for the
International Conference on Plasma Physics
Delhi, November 22-28, 1989

Department of Plasma Physics
The Royal Institute of Technology
S-100 44 Stockholm, Sweden

ABSTRACT

The electric field plays an important role in the complex plasma system called the magnetosphere. In spite of this, direct measurements of this quantity are still scarce except in its lowest-altitude part, *i.e.* the ionosphere. The large scale ionospheric electric field has been determined from measurements on the ground and in low satellite orbit. For most of the magnetosphere, our concepts of the electric field have mostly been based on theoretical considerations and extrapolations of the ionospheric electric field.

Direct, *in situ*, electric field measurements in the outer parts of the magnetosphere have been made only relatively recently. A few satellite missions, most recently the Viking mission, have extended the direct empirical knowledge so as to include major parts of the magnetosphere.

These measurements have revealed a number of unexpected features. The actual electric field has been found to have unexpectedly strong space and time variations, which reflect the dynamic nature of the system. Examples are given of measured electric fields in the plasmasphere, the plasmasheet, the neutral sheet, the magnetotail, the flanks of the magnetosphere, the dayside magnetopause and the auroral acceleration region.

1. Introduction

The magnetosphere is a plasma system of considerable complexity (Fig. 1). It includes a rich variety of plasma populations with a wide range of properties such as density and temperature. Thus, the density ranges from about 10^6 particles per cm^3 in the F-layer of the ionosphere to 0.01 or less in the polar plumes of the magnetotail - a range of 8 powers of 10. Temperatures range from less than 1000 K in the lower ionosphere, to millions K in the plasmasheet. Usually the ions and electrons have different temperatures because they are subject to different energization processes and the thermal coupling between them is poor.

It is now generally understood that electric fields play crucial roles in this plasma system, both for its macroscopic dynamics and for the various acceleration processes that characterize the system.

This is a relatively recent development. In the early years of the space age the electric field was generally considered a parameter of little interest. The reason was an almost universal belief that the space plasma could be described essentially in terms of ideal magnetohydrodynamics, because its electrical resistivity should, according to classical formulas, be negligible.

As a result, almost nobody took it seriously when Hannes Alfvén already in 1958 proposed that magnetic-field-aligned electric fields not only exist but also play a role in the auroral process through electrostatic acceleration of auroral primary electrons (Alfvén 1958). Only much later and in the face of massive observational indications has this mechanism become almost universally accepted.

Thus, the prejudice springing from generally accepted theories was one reason why for many years no electric field measurements were made in the space plasma. Another was the fact that the d c electric field is a parameter that is technically very difficult to measure, except in the comparatively dense plasma of the ionosphere. Therefore, the first measurements were made from rockets and low altitude satellites, whereas measurements at high altitude and in the outer magnetosphere came much later. Even today only a handful of missions have included electric field measurements in such regions.

2. Ionospheric electric fields derived from ground based observations

An early method of deriving large scale average electric potential distributions in the ionosphere used ground based magnetometry. From the magnetic field the electric current systems in the ionosphere were estimated and from these the electric fields and potentials were calculated using a conductivity model. This method is still in use and for its application a "magnetogram inversion technique" has been developed (Mishin et al. 1979). It is now also being used in conjunction with satellite data for synoptic studies (Mishin 1989).

For many years powerful radars have been used for determinig the large scale electric field in the ionosphere, either using the coherent scatter from drifting inhomogeneities or incoherent scatter. On the basis of radar measurements empirical models of the ionospheric elecric fields have been developed by e. g. Foster (1983, 1987) and Holt et al. (1987). Fig. 2 shows examples of potential distributions for different directions of the solar wind magnetic field (Foster 1987).

Data from the North Scandinavian incoherent scatter radar, EISCAT, were used by Fontaine et al. (1986) to derive magnetospheric electric potential patterns in an equatorial region between 4 and 10 Earth radii. The general appearance of the patterns is in agreement with that shown in Fig. 5, but varies from day to day depending on the geophysical situation. The authors also made comparisons with plasmapause positions determined with the geostationary satellite GEOS 2. They found that the outermost closed equipotential as determined from the EISCAT data agreed well with the plasmapause, as should be the case in not too disturbed times.

Recently, three years of data from the North Scandinavian incoherent scatter radar, EISCAT, have been used to determine electric potential distributions in the invariant latitude range 61 - 72 degrees Senior et al. (1989) using a technique developed by Alcaydé et al (1986). The results are reported to be in generally good agreement with earlier results from the Millstone Hill and Chatanika radars.

By an ingenious way of coding the EISCAAT radar, it has very recently become possible to use it for obtaining high time resolution measurements of the ionospheric electric field. Such measurements, reported by Häggström et al. (1989), Williams et al. (1989) and Opgenoort et al. (1989), have revealed very strong and highly variable electric fields in the F region (around 260 km altitude). Field strengths exceeding 100 mV/m were recorded, and large variations occurred on the time scale of the highest resolution (45 s). (Because of the one-point nature of the measurements, it was not possible to distinguish between time and space variations.) These results point to a solution of an apparent discrepancy by indicating that the ionospheric fields, too, exhibit the highly dynamic character found to be typical for the directly measured magnetospheric fields as described in later sections of this paper.

3. Low altitude in situ measurements

Direct measurements of the ionospheric electric field by means of double probes on the Orbiting Geophysical Observatory OGO 6 were used by Heppner (1977) to construct an empirical model of the average field for various directions of the solar wind magnetic field and different levels of geomagnetic disturbance as characterized by the Kp index. This model has been extended by Heppner and Maynard (1987) using Dynamics Explorer 2 data. They have derived average patterns for various directions of the solar wind magnetic field and for various levels of geomagnetic activity as measured by the K_p index. For example, when the solar wind magnetic field has a positive nortward component, the pattern can become very distorted as illustrated in Fig.3.

As, even for a low orbit satellite, the orbital period is 1 1/2 hours, the actual potential pattern can change substantially from one passage to another, and even during the passage. Therefore, the actual potential distribution prevailing at any given time can differ substantially from the average potential distributions derived from such passages.

4. "Instantaneous" potential patterns

Only recently have methods been developed for determining the ionospheric electric field distribution at a given time.

Kamide et al (1986) used ground based magnetometer date combined with a conductivity model based on UV images from a satellite (DE 2) to calculate the ionospheric electric field distribution (and also magnetic field aligned currents and Joule heating) with a resolution of 12 minutes.

Marklund et al. (1987, 1988) have developed a technique of calculating global electric field distributions using a combination of in situ measurements of electric fields, magnetic fields and particle fluxes, UV-pictures of the auroral luminosity taken from the same satellite and relevant ground based data. This empirical information is used as input to a realistic mathematical model of the electrodynamics of the ionospheric plasma, from which the global distribution of electric fields (and other, related quantities) can be calculated.

Fig. 4 shows a comparison of average potential contours derived from (a) ground based data and (b) from satellite data, as well as (c) an "instantaneous" distribution derived with the Marklund-Blomberg technique. The differences between the two former reflect the uncertainties involved. The third, being the distribution at a given time, differs, as it should, in details from the average distributions but agrees with them in general character, as it also should.

5. Extrapolation of ionospheric electric fields into the magnetosphere

The empirical models of ionospheric electric fields have been used to infer the electric fields in the outer magnetosphere by mapping them along magnetic field lines, assuming the latter to be electrical equipotentials. Such an extrapolation is illustrated in Fig. 5, which is typical of the perception of the electric fields expected in the equatorial plane of the magnetosphere. It is characterized by an inner region of closed electric potentials and outside of that a region with generally dawn-to-dusk directed electric field. The corresponding plasma convection is a corotation with the Earth in the inner region and a sunward flow outside it.

Although such extrapolation may give some insight into the broad characteristics of the electric field in the outer magnetosphere, its accuracy suffers from several serious sources of error.

(1) Insufficient knowledge of magnetic field line geometry

The magnetospheric magnetic field has been measured extensively, and sophisticated models have been constructed (for example Toffoletto and Hill 1986, Tsyganenko 1987, 1989). Although these models rather well reproduce the local electric field at a given point under given geophysical conditions, the magnetic conjugacy of widely separated points remains very uncertain, beacuse in the calculation of a magnetic field line even small systematic errors can give large errors in the location where the field line ends up.

(2) Electric induction fields

Especially under the most interesting geophysical conditions, such as magnetospheric substorms, the time variation of the magnetic field is strong enough to make the large scale electric field in the outer magnetosphere deviate substantially from a potential field and hence make equipotential mapping meaningless.

(3) Magnetic-field aligned electric fields

In the auroral acceleration region there exist magnetic-field aligned components of electric fields, and hence the magnetic field lines are not equipotential (although the error from this source is usually small compared to the total potential difference across the magnetosphere).

6. Whistler data

In the relatively dense plasma region called the plasmasphere the azimuthal electric fields can be deduced from analysis of a kind of naturally occurring electromagnetic waves in the audio frequency range, called whistlers. These are generated by lightening discharges and propagate from one hemisphere to the other along magnetic-field aligned plasma irregularities, so-called ducts. When such a duct drifts radially due to an electric field, the radial velocity of the duct and hence the azimuthal electric field can be calculated from analysis of the whistler waves carried by the duct, although difficulties arise in situations where the curl of the electric field cannot be neglected (Block and Carpenter 1974).

In the limited region where this method applies, it gives results that are in general agreement with the electric field shown in Figure 5.

7. Deductions from energetic particle measurements

Energetic particle measurements have been performed in the outer magnetosphere much more extensively than direct electric field measurements. They allow certain inferences about the electric fields, too. A particularly interesting possibility is provided by the fact that clouds of energetic particles get injected in the nightside magnetosphere and then perform a gradient and curvature drift around the Earth. As the electric field drift adds to the energy-dependent gradient and curvature drift, systematic analysis of observed velocity dispersions allows reconstruction of the average electric field in the region concerned. A model of the average electric field in the equatorial plane was developed by McIlwain (1972), who has more recently published an improved, Kp-dependent model (McIlwain 1986). An example of equipotentials is shown in Figure 6. It shows, although for a smaller region and with less detail, the same general features as those in Figure 5.

8. Results of direct measurements

Direct measurements of electric fields at high altitude were made with the American satellite S3-3 (to 8 000 km) in 1976 and the Swedish satellite Viking (to more than 13 000 km) in 1986. Measurements extending to several Earth radii were made in 1977 by the European satellite GEOS-1. This was followed by ISEE-1 (with an apogee of about 22 Earth radii) in 1977, then GEOS-2 in 1978.

The results of these missions have confirmed some of the preexisting expectations, such as the corotational field and the existence, in an average sense, of a dawn-to-dusk electric field in the equatorial plane. However, they have alsobrought many unexpected discoveries and shown that themagnetospheric electric field has much more dramatic variations in space as well as in time than had been anticipated, and shows a complexity greatly exceeding that of the magnetic field. This also means that it is much more difficult - if at all meaningful - to quantitatively model the electric field.

The following sections will be devoted to characterizing the electric fields observed in the various parts of the magnetosphere.

9. The plasmasphere

The relatively dense plasma of the plasmasphere makes this region the electrodynamically least complicated one outside the ionosphere, of which it can be considered an extension. For example, collisions are frequent enough that one should expect a Generalized Ohm's law to hold. The electric polarization field of the rotating ionosphere presents an electric polarizarion field of several tens of kV to space above. But because of the good electrical contact this only causes the plasmasphere to corotate and thereby polarize in the same way.

However, even this simple part of the magnetosphere is not entirely free from surprises. Fig. 7 compares the plasmaspheric electric field actually measured by GEOS-1 with the electric field corresponding to corotation (Pedersen et al. 1984).

It shows that the theoretically expected corotation prevails in the inner parts, but also that substantial, still unexplained deviations occur in the outer parts. (Curve 1 is a model field representing perfect corotation. Curve 2 is a model field without any corotation at all).

Especially during disturbed conditions large deviations from co-rotation are observed near the plasmapause (Maynard et al. 1983). Just inside the dusk side of the plasmapause electric fields many times stronger than the co-rotational field, and oppositely directed, have been observed with GEOS-2 (Pedersen, private communication). During a substorm very strong electric fields were observed adjacent to and just outside the plasmapause. The field strength projected to ionospheric level exceeded 100 mV m^{-1}, and the event was accompanied by significant penetration of the convection electric field inside the plasmapause (Maynard et al. 1980, 1982). These observations of strong subauroral electric fields in the magnetosphere are in agreement with what could be expected on the basis of earlier, rocket-borne measurements (cf. Fahleson et al. 1971).

10. The plasmasheet

Although the dawn-to-dusk electric field expected from extrapolations of the inospheric electric field seems to exist in an average sense, the actual electric field inthe plasma sheet has been found to be extremely variable, and this greatly reduces the relevance of the average field.

During geomagnetically quiet times the electric field is usually too weak to be measured with the double probe instruments flown so far, i. e. less than a few tenths of mV/m. Finite small values have, however, been measured with the electron beam technique (Baumjohann et al. 1985).

During geomagnetically active times, especially during the substorm expansive phase, the electric fields are much stronger and very variable in space and time (Aggson et al. 1983a, Pedersen et al. 1985). An example of electric fields measured in the plasma sheet is shown in Fig. 8. Under such conditions induction electric fields are also important, which means that there does not even exist an electric potential in the plasmasheet.

For a certain period of time the simultaneous operation of GEOS-2 and ISEE-1 allowed two-point measurements in the plasmasheet. This allowed the detection of propagating disturbances, such as the example shown in Fig. 9. Such disturbances were usually found to propagate toward the Earth, and from an analysis of the delay time it was found that the speed of propagation was approximately equal to the average Alfvén velocity in the intervening region.

Very strong electric fields occur especially near the plasma-sheet boundary, where field strengths of several tens of mV/m have been measured. As shown by Pedersen et al. (1985), these electric fields are of an inductive nature, in agreement with predictions by Heikkila et al. (1979).

Even stronger fields - over 100 mV/m - were occasionally observed with ISEE 1 near the poleward boundary of the plasma sheet. These are considered to be high altitude cases of so-called electrostatic shocks (Mozer et al. 1977) which are prevalent in the auroral acceleration region, as will be discussed in Section 15 below. As illustrated in Fig. 10 the strength of these electricfields (which are transverse to the magnetic field) is essentially independent of geocentric distance instead of decresing with distance from the Earth as equipotential mapping would require.

11. The neutral sheet

In the neutral sheet, too, the electric field is very different during quiet and disturbed times. In the former case the electric field is typically less than =.5 mV/m. In disturbed times, however, the neutral sheet electric field is very irregular and often quite strong. This is illustrated in Fig. 11, which shows the dawn to dusk component of the electric field (upper panel) and the sunward magnetic field component (lower panel), which changes sign as the satellite crosses the neutral sheet. The figure shows a quiet time north to south crossing at 16.30 UT with unobservably small electric field and a disturbed time south to north crossing in the 20.00 to 20.30 UT time interval with large irregular electric fields. Cattell and Mozer (1986) have identified the dominating wave mode as lower hybrid and suggest that the wave activity is sufficient to provide a substantial anomalous resistivity.

12. The magnetospheric tail

In the central tail lobes of the magnetotail the plasma density is usually too low to allow satisfactory operation of the double probes. However, in parts of the tail measurements have been possible and have been confirmed by particle measurements, that show anisotropies due to the associated ExB/B^2 drift. One result of such measurements was the discovery of "vortices" (Birn et al. 1985), of which an example is shown in Fig 12.

13. The flanks of the magnetosphere

A still controversial issue is whether in adition to the general dawn-to-dusk electric field in the equatorial plane, there exists an oppositely directed field in the outer flanks of the magnetosphere. Such a field is expected, if so-called viscous interaction between the solar wind and magnetosphere is important for the transfer of momentum and energy into the magnetosphere. Mozer (1984) has reported such a field as illustrated in Fig. 13. A dusk-to-dawn electric field (negative E_y) is seen just inside the magnetopause (identifyable by the transition from negative to positive magnetic field in the bottom panel). He has also concluded that it is relatively insignificant, having a total potential that is only about 10% of the potential of the dawn-to-dusk field, but the precise value and its significance has been contested by Heikkila (1986); see also Mozer 1986).

14. The dayside magnetopause

A key issue in magnetospheric physics has been whether the magnetopause is an electric potential (Heikkila 1975) as in toplogically closed magnetospheric models of the Axford and Hines (1961) type, or has a significant dawn-to-dusk directed tangential component of electric field as envisaged in open magnetospheric models of the kind proposed by Dungey (1961).

One of the surprising results of the direct measurements at the dayside magnetopause was that the magnetopause electric field has so violent fluctuations that the d c tangential component is usually overshadowed. Single cases have been found, where the d c tangential electric field stands out fairly clearly (Mozer et al. 1979), but that is exceptional. However, from a statistical study, Lindqvist and Mozer (private communication) have confirmed the existence of a non-vanishing average dawn-to-dusk directed tangential electric field component at the dayside magnetopause.Its magnitude is of the order of a few mV/m and it is positively correlated with the strength of the southward component of the solar wind magnetic field. This is in agreement with the measurements of Baumjohann and Haerendel (1985) of the internal dawn-to-dusk electric field. Occasional large electric fields at magnetopause rotational discontinuities have been reported by Aggson et al. (1983b).

The unexpected large fluctuations of the magnetopause electric field, discovered with ISEE-1, are probably more important for the understanding of magnetospheric dynamics than the average d c electric field that has been at the focus of prevailing theoretical models. The discovery shows that the physics of the magnetopause is far more complex than envisaged in current "reconnection" models. For example, the fluctuating electric fields are probably essential for the observed entry of magnetosheath plasma into the magnetosphere, as suggested by Lemaire (see Lemaire 1985 and references therein; Heikkila 1982a,b and Lundin 1984).

15. The auroral acceleration region

In terms of plasma physics the probably most interesting part of the Earth's magnetosphere is the auroral acceleration region. Its location in space was discovered relatively late, and the first systematic direct measurements in this region were made in 1977 by the US satellite S3-3. It led to two major discoveries: (1) "electrostatic shocks" and (2) multiple electric double layers.

The electrostatic shocks (Mozer *et al*. 1977) are regions of very strong - over 100 mV/m electric fields predominantly transverse to the magnetic field. They sometimes, but not always, occur inpairs. Their horizontal extent is of the order of a few km and their potentials a few kV. S3-3 observed them up to its apogee altitude of 8 000 km, but ISEE-1 has observed occasional cases out to over 7 Earth radii (cf. Fig. 10). The fact that such strong electric fields exist at high altitude but not in the ionosphere means that there must be magnetic-field aligned electric fields somewhere inbetween.

The most detailed observations of electrostatic structures of this kind have been made with the Swedish satellite Viking, which also extended the observed altitude range to over 13 000 km. It revealed an even more complex fine structure than known before (Block *et al*. 1987a,b; Fälthammar *et al*. 1987). An example of an electric field structur of the "electrostatic shock" type is showm in Fig. 14. In this case electric fields with a peak strength of 150 mV/m are directed inwards from both sides, and the total potential is about a kV (negative in the middle). Variation of this kind along the orbit of the satellite is considered to be the signatures of U-shapedequipotentials in the auroral acceleration region as schematically illustrated in Fig. 15. Such potential structures accelerate electrons downward to cause the aurora as well as ions upward to form the outgoing ion beams that are commonly seen above auroras. Such beams contribute to populating the magnetosphere with ionospheric O^+ ions during magnetically disturbed times.

An outstanding feature in the Viking electric field data is the prevalence of extremely strong and irregular electric fields above the auroral oval. The occurrence of such electric fields is well correlated with regions of electron precipitation as illustrated in Fig. 16. The regular sinusoidal variations at the satellite spin frequency reflect steady sub-auroral electric fields. Over the auroral oval very strong and irregular electric fields occur in the same regions where precipitating accelerated electrons are also observed.

The observed large and rapid fluctuations are electrostatic in the sense that there are no corresponding variations of any significance in the magnetic fields. (The upper limit of the magnetic field fluctuations that is much lower than the electric field fluctuations divided by the Alfvén velocity. Even though the Alfvén-velocity in some parts of the Viking orbit is extremely high, often exceeding 10 000 km/s, such magnetic variations would have been easily observed.)

The transition from the quiet and usually weak (a few mV/m subauroral electric fields to the large and irregular electric fields of the auroral acceleration region is often extremely sharp. An example is given in Fig. 17, where the transition occurs in a small fraction of a second, corresponding to less than a km of satellite path.

The other S3-3 discovery concerning the electric field was that of numerous weak electric double layers (Temerin _et al_. 1982; Mozer and Temerin 1983) a phenomenon predicted by Block (1972). Although each double layer had apotential of only a fraction of a volt, they occurred in largenumbers. It was concluded that they may account for anaccumulated potential drop of several kV along a magnetic fieldline in the auroral acceleration region. The S3-3 observations ofnumerous weak double layers as well as the conclusion justmentioned have been confirmed with the Viking satellite (Boström _et al_ 1987).

16. Concluding remarks

The electric field is a parameter of key importance in magnetospheric physics. After having long been ignored it has now been measured by at least a few satellites. This has improved our knowledge in very important ways, but many more measurements are needed before the magnetospheric electric field is known as well as its importance justifies.

References

Aggson, T.L., Heppner, J.P., and Maynard, N.C., 1983a, Observations of Large Magnetospheric Electric Fields During the Onset Phase of a Substorm, J. Geophys. Res., 88, 3981

Aggson, T.L., Gambardella, P.J. and Maynard, N.C., 1983b, Electric Field Measurements at the Magnetopause. 1. Observation of Large Convective Velocities at Rotational Magnetopause Discontinuities, J. Geophys. Res., 88, 10 000

Alcaydé, D. Caudal, G., and Fontamari, J., 1986, Convection Electric Fields and Electrostatic Potential Over $61^o < < 72^o$ Invariant Latitude Observed with the European Incoherent Scatter Facility, 1. Initial Results, J. Geophys. Res., 91, 233-247

Alfvén, H., 1958, On the Theory of Magnetic Stoms and Aurorae, Tellus, 10, 104

Axford, W.I. and Hines, C.O., 1961, A Unifying Theory of High-Latitude Geophysical Phenomena and Geomagnetic Storm, Canad. J. Phys., 39, 1433

Baumjohann, W., Haerendel, G., and Melzner, F., 1985, Magnetospheric Convection Observed Between 0600 and 2100 LT: Variations With K_p, J. Geophys. Res., 90, 393

Baumjohann, W. and Haerendel, G., 1985, Magnetospheric Convection Observed Between 0600 and 2100 LT: Solar Wind and IMF Dependence, J. Geophys. Res., 90, 6370

Birn, J., Hones, E.W., Jr., Bame, S.J., and Russell, C.T., 1985, Analysis of 16 Plasma Vortex Events in the Geomagnetic Tail, J. Geophys. Res., 90, 7449

Block, L.P., 1972, Potential Double Layers in the Ionosphere, Cosmic Electrodynamics, 3, 349-376.

Block, L.P. and Carpenter, D.C., 1974, Derivation of Magnetospheric Electric Fields from Whistler Data in a Dynamic Geomagnetic Field, J. Geophys. Res., 79, 2783, 1974.

Block, L.P., Fälthammar, C.-G., Lindqvist, P.-A., Marklund, G.T., Mozer, F.S., Pedersen, A., Potemra, T.A., and Zanetti, L.J., 1987a, Electric Field Measurements on Viking: First Results, Geophys. Res. Lett., 14, 435

Block, L.P., Fälthammar, C.-G., Lindqvist, P.-A., and Marklund, G.T., 1987b, Parallel Electric Fields: Viking Observations and Interpretation, Extended Abstract to invited lecture at the International Symposium of Quantitative Modelling of Magnetosphere-Ionosphere Coupling, Kyoto, 9-13 March

Boström, R., Koskinen, H., and Holback, B., 1987, Low Frequency Waves and Small Scale Solitary Structures, Proc. 21st ESLAB Symposium, 22-25 June 1987, Bolkesjø, Norway, ESA SP-275

Cattell, C.A. and Mozer, F.S., 1982, Electric Fields Measured by ISEE-1 Within and Near the Neutral Sheet During Quiet and Active Times, Geophys. Res. Lett., 9, 1041

Cattell, C.A. and Mozer, F.S., 1986, Experimental Determination of the Dominant Wave Mode in the Active Near-Earth Magnetotail, Geophys. Res. Lett., 13, 221

Dungey, J.W., 1961, Interplanetary Magnetic Field and the Auroral Zones, Phys. Rev. Lett., 6, 47

Fahleson, U., Fälthammar, C.-G., Pedersen, A., Knott, K., Brommundt, G., Schumann, G., Haerendel, G. and Rieger, E., 1971, Simultaneous Electric Field Measurements Made in the Auroral Ionosphere by Using Three Independent Techniques, Radio Sci., 6, 233

Fontaine, D., Perraut, S., Alcaydé, D., Caudal, G., and Higel, B., 1986, Large Scale Structures of the Convection Inferred from Coordianted Measurements by EISCAT and GEOS 2, J. Atmos. Terr. Phys., 48, 973-986

Foster, J. C., 1983, An Empirical Electric Field Model Derived from Chatanika Radar Data, J. Geophys. Res., 88, 981-987

Foster, J. C., 1987, Radar-Deduced Models of the ConvectionElectric Field, Proc. Internat. Symposium on Quantitative Modeling of Magnetosphere Ionosphere Coupling Processes, Eds. Y. Kamide and R. A. Wolf, Kyoto, Japan, 71-76

Fälthammar, C.-G., Block, L.P., Lindqvist, P.-A., Marklund, G.T., Pedersen, A., and Mozer, F.S., 1987, Preliminary Results from the D.C. Electric Field Experiment on Viking, Ann. Geophys., 5A, 171

Heppner, J. P., 1977, Empirical models of High-Latitude Electric Fields, J. Geohys. Res., 82, 1115

Heppner, J. P., and Maynard, N. C., 1987, Empirical High-Latitude Electric Fields, J. Geophys. Res., 92, 4467-4489

Heikkila, W.J., 1975, Is There an Electrostatic Field Tangential to the Dayside Magnetopause and Neutral Line?, Geophys. Res. Lett., 2, 154

Heikkila, W.J., 1982a, Inductive Electric field at the Magnetopause, Geophys. Res. Lett., 9, 877

Heikkila, W.J., 1982b, Impulsive Plasma Transport Through the Magnetopause, Geophys. Res. Lett., 9, 159

Heikkila, W.J., 1986, Comment on Electric Field Evidence on the Viscous Interaction at the Magnetopause, by F.S. Mozer, Geophys. Res. Lett., 13, 233

Heikkila, W.J., Pellinen, R.J., Fälthammar, C.-G., and Block, L.P., 1979, Potential and Inductive Electric Fields in the Magnetosphere During Auroras, Planet. Space Sci., 27, 1383

Holt. J. M., Wand, R. H., Evans, J. V., and Oliver, W. L.,1987, Empirical Models for the Plasma Convection at High Latitudes From Millstone Hill Observations, J. Geophys. Res., 92, 203-212

Häggström, I., Opgenoorth, H., Williams, P.J.S., Jones, G.O.L., and Schlegel, K., 1989, Applications of Alternating Codes for EISCAT Observations During ERRIS, preprint

Kamide, Y., Craven, J. D., Frank, L. A., Ahn, B.-H., and Akasofu, S.-I., 1986, Modeling Substorm Current Systems Using Conductivity Distributions Inferred from DE Auroral Images,J. Geophys. Res., 91, 13506-13512

Lemaire, J., 1985, Plasmoid Motion Across a Tangential Discontinuity with application to the magnetopause, J. Plasma Phys., 33, 425

Lundin, R., 1984, Solar Wind Energy Transfer Regions Inside the Dayside Magnetopause. II. Evidence for an MHD Generator Process, Planet. Space Sci., 32, 757

Maynard, N.C., Aggson, T.L. and Heppner, J.P., 1980, Magnetospheric Observations of Large Sub-Auroral Electric Fields, Geophys. Res. Lett., 7, 881

Maynard, N.C., Aggson, T.L. and Heppner, J.P., 1983, The Plasmaspheric Electric Field Measured by ISEE 1, J. Geophys. Res., 88, 3991

Maynard, N.C., Aggson, T.L. and Egeland, A., 1982, Intense Variable Electric Fields at Ionospheric Altitudes in the High Latittude Regions Observed by DE-2. Geophys. Res. Lett. 9, 981

Marklund, G.T., Blomberg, L. G., Potemra, T. A., Murphree,J. S., Rich, F. J., and Stasiewicz, K., 1987, A New Method toDerive "Instantaneous" High-Latitude PotentialDistributions from Satellite Measurements Including AuroralImager Data, Geophys. Res. Lett., 14, 439-442

Marklund, G. T., Blomberg, L. G., Stasiewicz, K., Murphree,Pottelette, R., Zanetti, L. J., Potemra, T. A., Hardy, D.A., and Rich, F. J., 1988, Snapshots of High-LatitudeElectrodynamics Using Viking and DMSP F7 Observations, J. Geophys. Res. 93, 14479-14492

McIlwain, C.E., 1986, A Kp Dependent Equatorial Electric Field Model, Adv. Space Res., 6, 187

Mishin, V.M, Bazarzhapov, A.D., Shpynev, G.B., 1979, Dynamics of the Magnetosphere, Ed. S.I. Akasofu, D. Reidel Publ. Co., Dordrecht, Holland, p. 249.

Mishin, V.M. Submitted to Space Sci. Rev. 1989

Mozer, F.S., 1981, ISEE-1 Observations of Electrostatic Shocks on Auroral Zone Field Lines Between 2.5 and 7 Earth Radii, Geophys. Res. Lett., 8, 823

Mozer, F.S., 1984, Electric Field Evidence on the Viscous Interaction at the Magnetopause, Geophys. Res. Lett., 11, 135

Mozer, F.S., 1986, Reply to Heikkila, Ceophys. Res. Lett., 13, 235

Mozer, F.S. and Temerin, M., 1983, Solitary Waves and Double Layers as the Source of Parallel Electric Fields in the Auroral Acceleration Region, High-Latitude Space Plasma Physics, Ed. B. Hultqvist and T. Hagfors, Plenum Press, New York, p. 453

Mozer, F. S., Carlsson, C. W., Hudson, M. K., Torbert, R. B.,Parady, B., Yatteau, J., and Kelley, M. C., 1977, Observations of Paired Electrostatic Shocks in the Polar Magnetosphere, Phys Rev. Lett., 38, 292

Mozer, F.S., Torbert, R.B., Fahleson, U.V., Fälthammar, C.-G., Gonfalone, A., Pedersen, A., and Russell, C.T., 1979, Direct Observation of a Tangential Electric Field Component at the Magentopause, Geophys. Res. Lett., 6, 305

Opgenoorth, H.J., Haggstrom,I., Williams, PF.J.S., Jones, B, and Providiakes, S., 1989, Observations of Strong Electric Fields and Associated Elevations of E-Region Electron Temperatures in the Close Vicinity of Auroral Arcs, Abstract for the Fall AGU

Pedersen, A., Cattell, C.A., Fälthammar, C.-G., Formisano, V., Lindqvist, P.-A., Mozer, F.S., and Torbert, R., 1984, Quasistatic Electric Field Measurements with Spherical Double Probes on the GEOS and ISEE Satellites, Space Sci. Rev., 37, 269

Pedersen, A., Cattell, C.A., Fälthammar, C.-G., Knott, K., Lindqvist, P.-A., Manka, R.H., and Mozer, F.S., 1985, Electric Fields in the Plasma Sheet and Plasma Sheet Bourdary Layer, J. Geophys. Res., 90, 1231

Temerin, M., Cerny, K., Lotko, W., and Mozer, F.S., 1982, Observations of Double Layers and Solitary Waves in the Auroral Plasma, Phys. Rev. Lett., 48, 1175

Toffoletto, F.R. and Hill, T.W., 1976, Quantitative Model of Magnetic Coupling between Solar Wind and Magnetosphere, Solar Wind-Magnetosphere Coupling, Eds. Y. Kamide and J.A. Slavin, Terra Publishing Company, Tokyo, p. 275.

Tsyganeko, N.A., 1987, Global Quantitative Models of the Geomagnetic Field in the Cislunar Magnetosphere for Different Disturbance Levels, Planet. Space Sci., 35, 1347

Tsyganenko, N. A., 1989, A Magnetospheric Magnetic Field Model With a Warped Tail Current Sheet, Planet. Space Sci, 37,5-20

Williams, P.J.S., Jones, G.O.L., Jones, B., Ophgenoorth, H., and Häggström, I., 1989, High Resolution Measurements of Magnetospheric Electric Fields, preprint.

Captions to the Figures

Fig. 1. The structure of the magnetosphere.

Fig. 2. Examples of equipotential contours of the average ionospheric electric field for magnetic configurations in the solar wind (Foster 1987). By is the dawn-to-dusk component and Bz the northward component.

Fig. 3. Examples of potential patterns based on OGO 6 and DE 2 data for weak (a) and strong (b) northward component of the solar wind magnetic field (Heppner and Maynard, 1987).

Fig. 4. Comparison of ionospheric potential distributions.
a) Average distribution according to Foster's (1987) model
b) Average distribution according to Heppner's and Maynard's (1987) model
c) "Instantaneous" distribution derived from the Marklund-Blomberg model (Marklund et al. 1988)

Fig. 5. Equipotential contours of large scale electric field in the ionosphere and the corresponding equipotentials of the same field extrapolated into the equatorial plane (Foster 1987).

Fig. 6. Example of average electric equipotentials in the equatorial plane of the magnetosphere according to the model of McIlwain (1986) for $K_p = 2$.

Fig. 7. Magnitude and direction of GEOS-1 spin plane component of the electric field for an inbound pass through the plasmasphere (Pedersen et al. 1984).

Fig. 8. Example of electric field measured in the plasmasheet (Pedersen et al. 1984)

Fig. 9. Electric field observed both at ISEE-1 and GEOS-2 (Pedersen et al. 1985)

Fig. 10. Peak electric field strength in electrostatic shocks observed with ISEE 1 (Mozer 1981)

Fig. 11. Dawn-to-dusk component of the electric field (upper panel) and sunward component of the magnetic field (lower panel) observed with ISEE-1 in the neutral sheet (Cattell and Mozer 1982)

Fig. 12. Variation of the direction of plasma flow in a "vortex" event in the magnetospheric tail (Birn et al. 1985)

Fig. 13. The dawn-to-dusk component, E_y (upper panel), of electric field and northward magnetic field, B_z, (lower panel) measured with ISEE-1 near the dawn flank of the magnetosphere (Mozer 1984).

Fig. 14. Close-up of an electric structure of the "electrostatic shock" type as observed with the Viking satellite (Fälthammar et al. 1987)

Fig. 15. Schematic representation of (distorted) U-shaped equipotentials in the auroral acceleration region.

Fig. 16. Electric field signal (in the frame of the spinniing satellite) during a nightside crossing above the auroral oval by the Viking satellite (Fälthammar et al. 1987).

Fig. 17. Example of sharp transition from quiet subauroral electric field to strong and rapidly varying electric fields characteristic of the auroral acceleration region (Fälthammar et al. 1987).

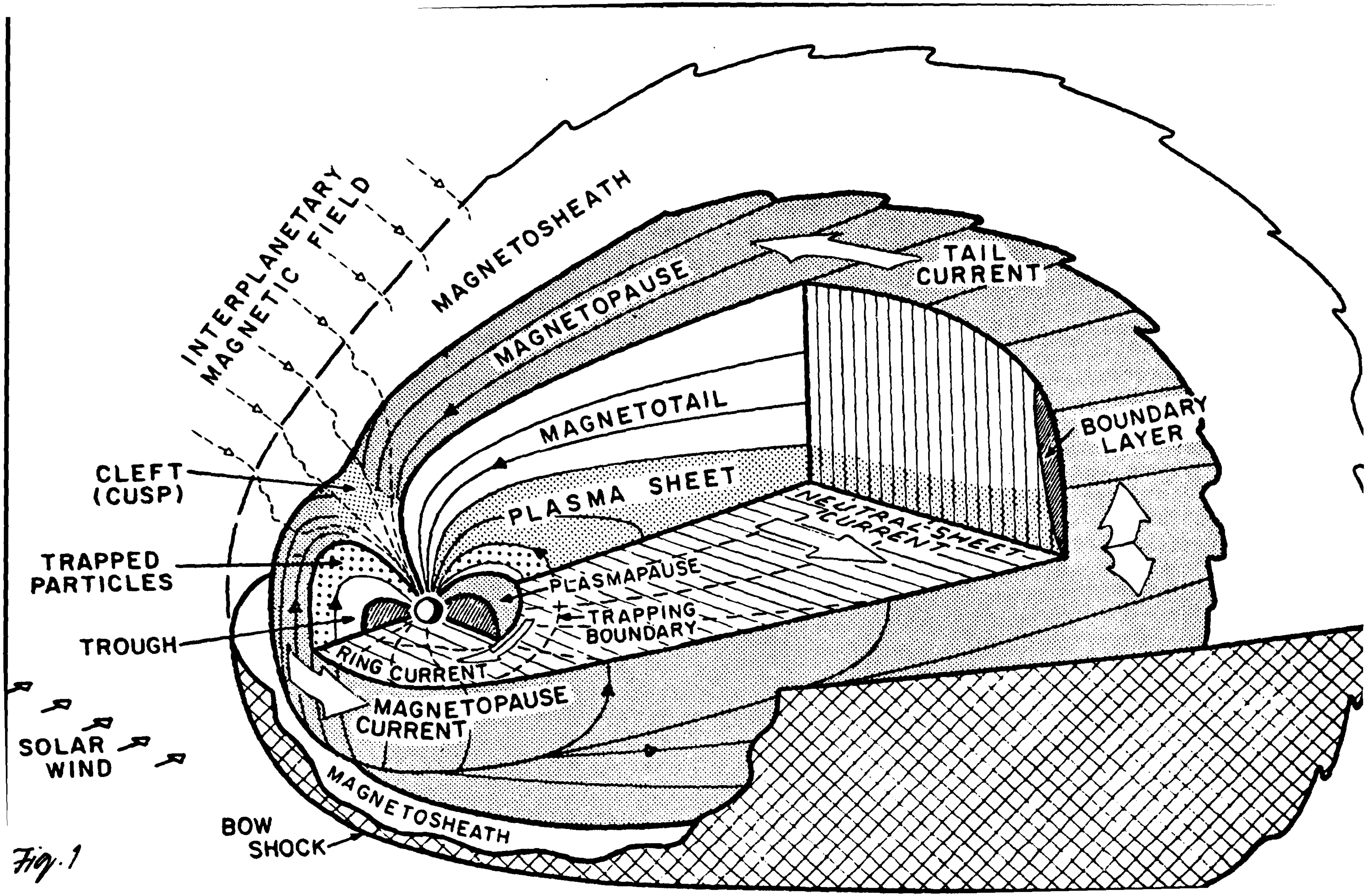

INTERPLANETARY
MAGNETIC
FIELD
MAGNETOSHEATH
MAGNETOPAUSE
TAIL
CURRENT
MAGNETOTAIL
BOUNDARY
LAYER
CLEFT
(CUSP)
PLASMA SHEET
NEUTRAL SHEET
CURRENT
TRAPPED
PARTICLES
PLASMAPAUSE
TRAPPING
BOUNDARY
TROUGH
RING CURRENT
MAGNETOPAUSE
CURRENT
SOLAR
WIND
MAGNETOSHEATH
BOW
SHOCK

Fig. 1

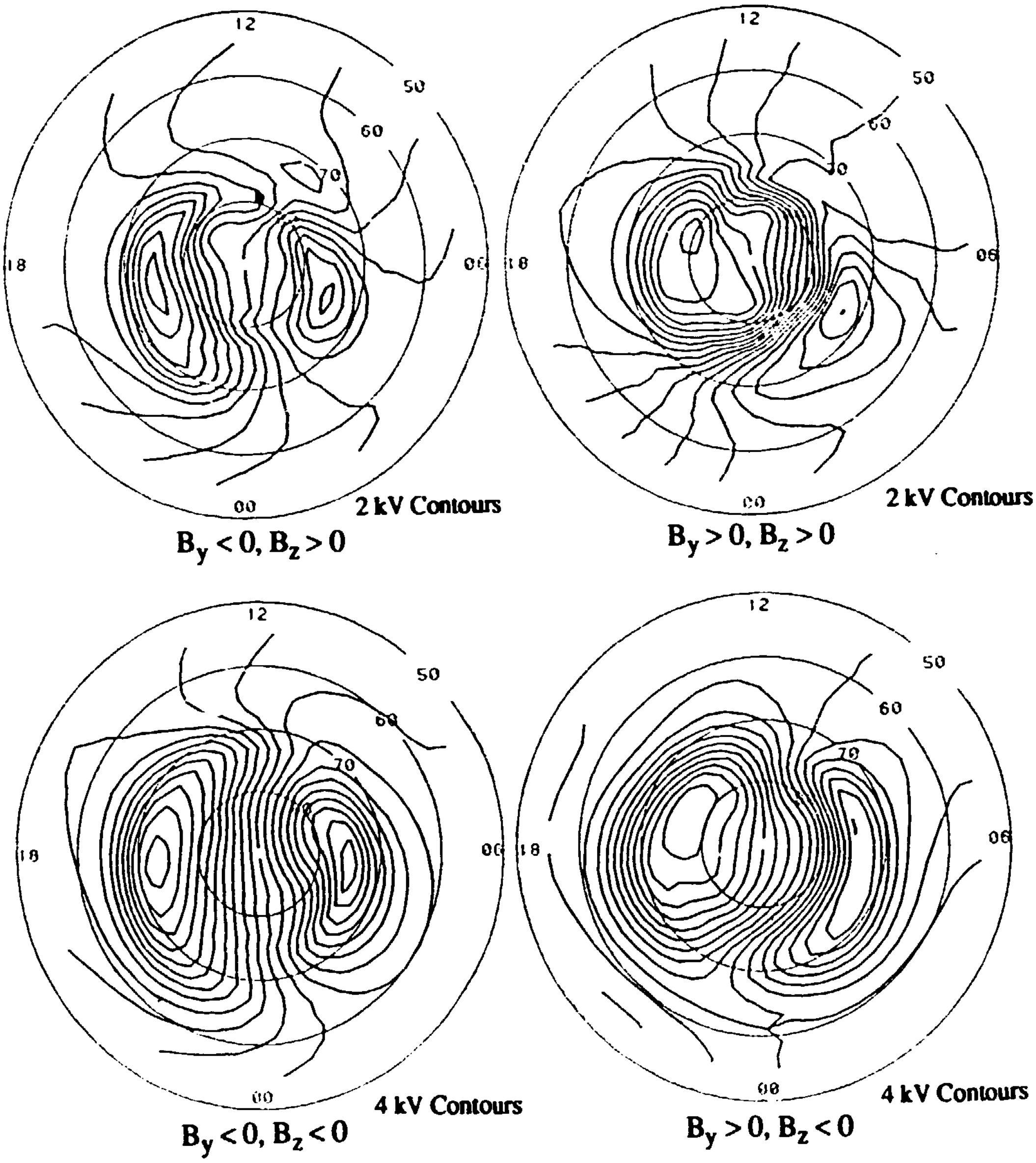

12
50
60
70
18
06
00
2 kV Contours
B_y < 0, B_z > 0
B_y > 0, B_z > 0
4 kV Contours
B_y < 0, B_z < 0
B_y > 0, B_z < 0

Fig. 2

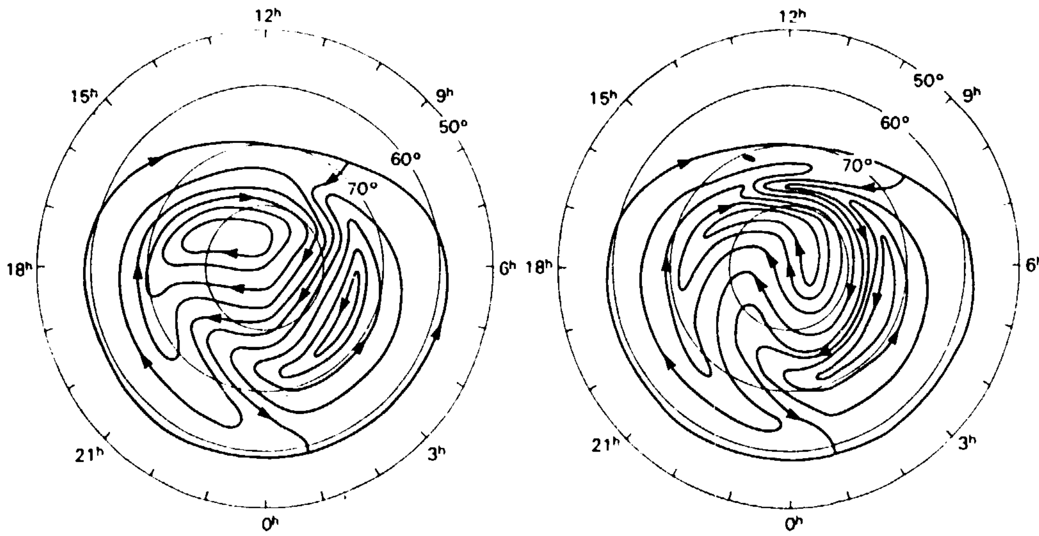
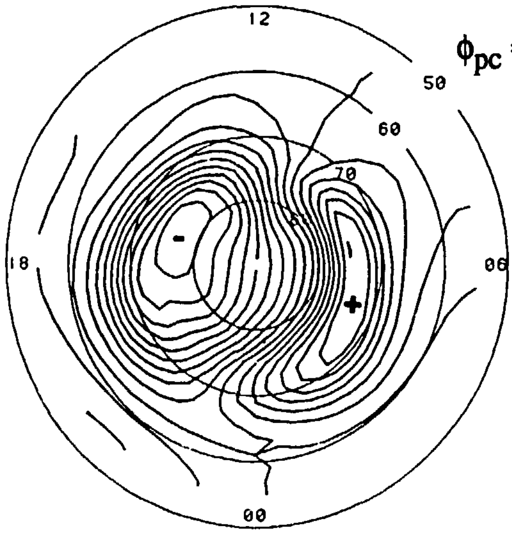

12h
15h
9h
50°
60°
70°
18h
6h
21h
3h
0h
12h
15h
50°
9h
60°
70°
18h
6h
21h
3h
0h

Fig. 3

STATISTICAL CONVECTION PATTERNS

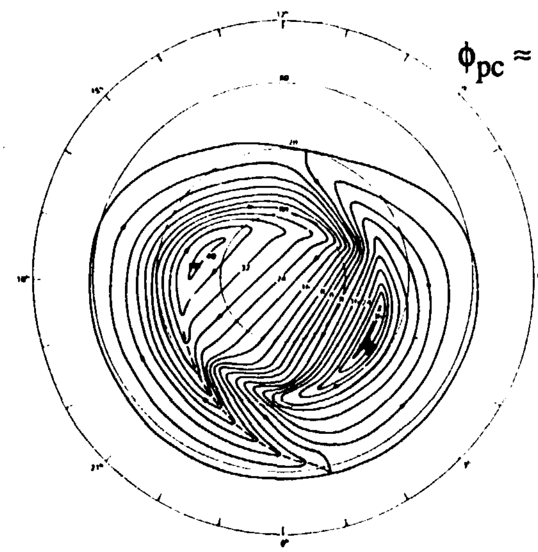
INCOMERENT RADAR DATA

SATELLITE DATA



$\phi_{pc} \approx 65$ kV

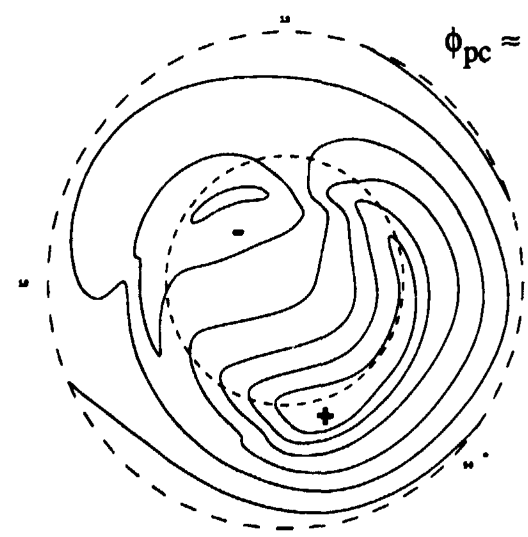
Foster, 1987



$\phi_{pc} \approx 76$ kV

Heppner and Maynard, 1987

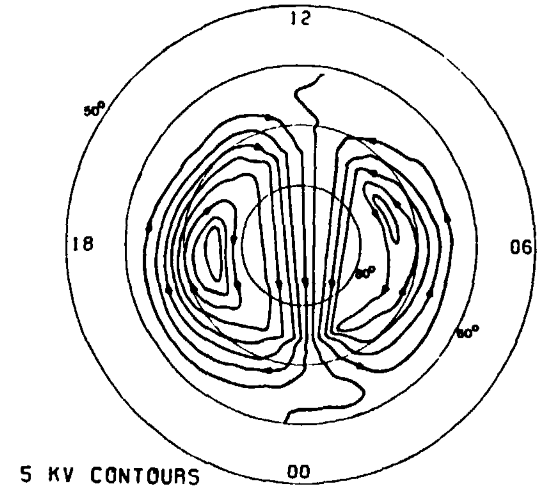
"INSTANTANEOUS" CONVECTION PATTERN



$\phi_{pc} \approx 60$ kV

IONOSPHERE

Fig. 4



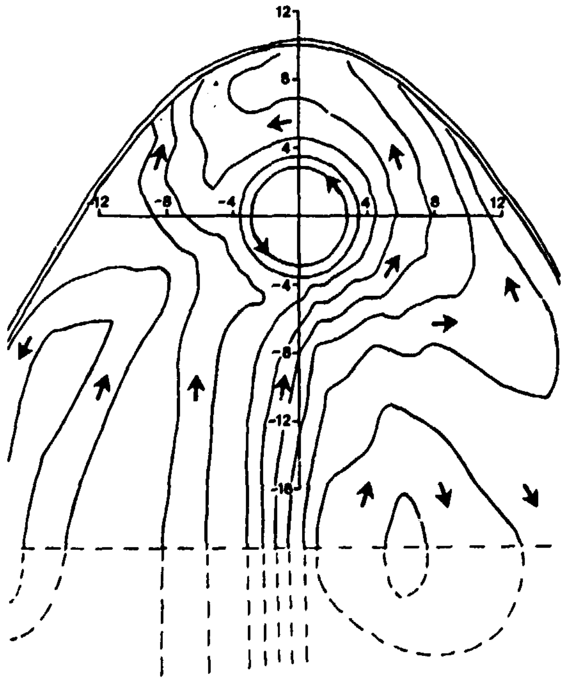


Fig.5

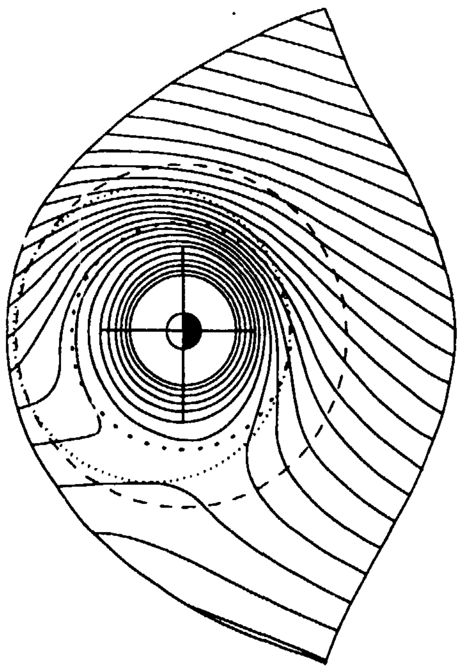


Fig. 6

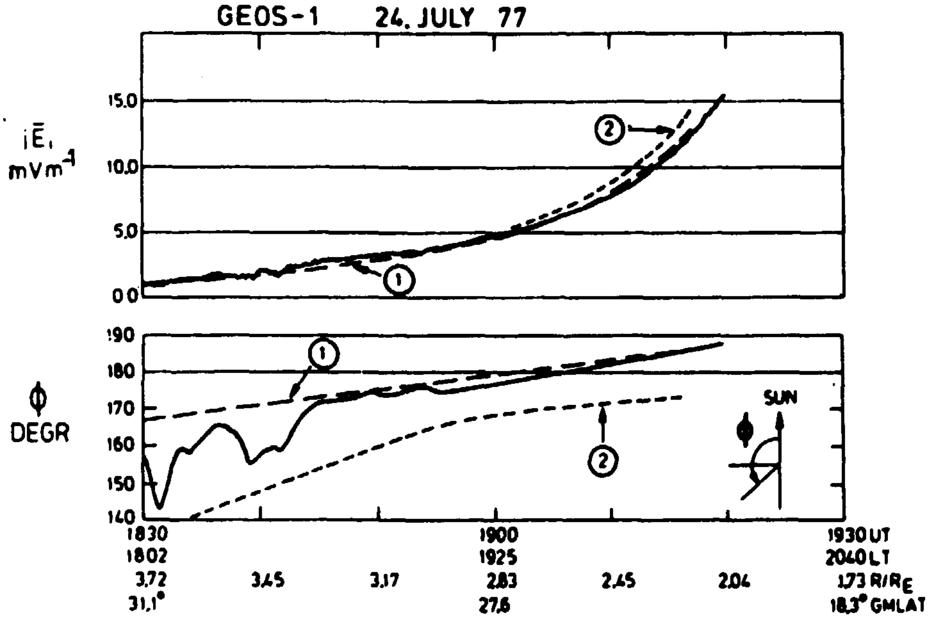
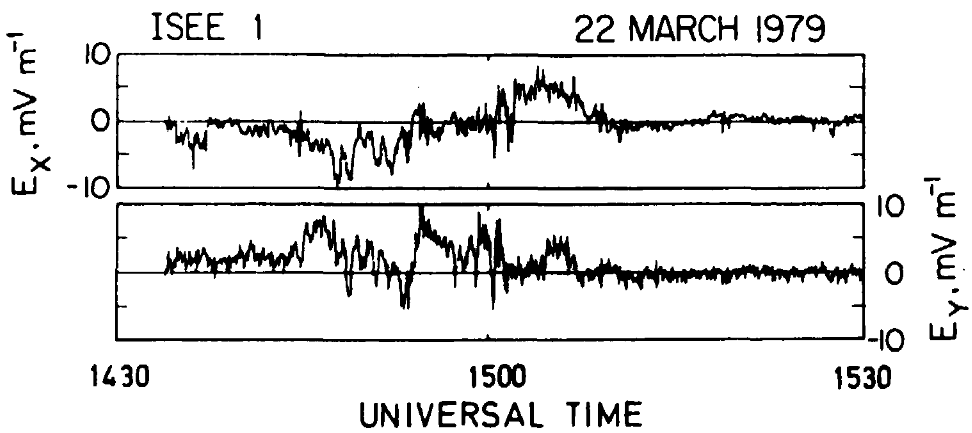

GEOS-1 24. JULY 77
|E|
mVm⁻¹
15.0
10.0
5.0
0.0
190
180
170
160
150
140
Φ
DEGR
SUN
1830
1802
3.72
31.1°
3.45
3.17
1900
1925
2.83
27.6
2.45
2.04
1930 UT
2040 LT
1.73 R/RE
18.3° GMLAT

Fig. 7



ISEE 1
22 MARCH 1979
E_X, mV m^-1
10
0
-10
E_Y, mV m^-1
10
0
-10
1430
1500
1530
UNIVERSAL TIME

Fig. 8

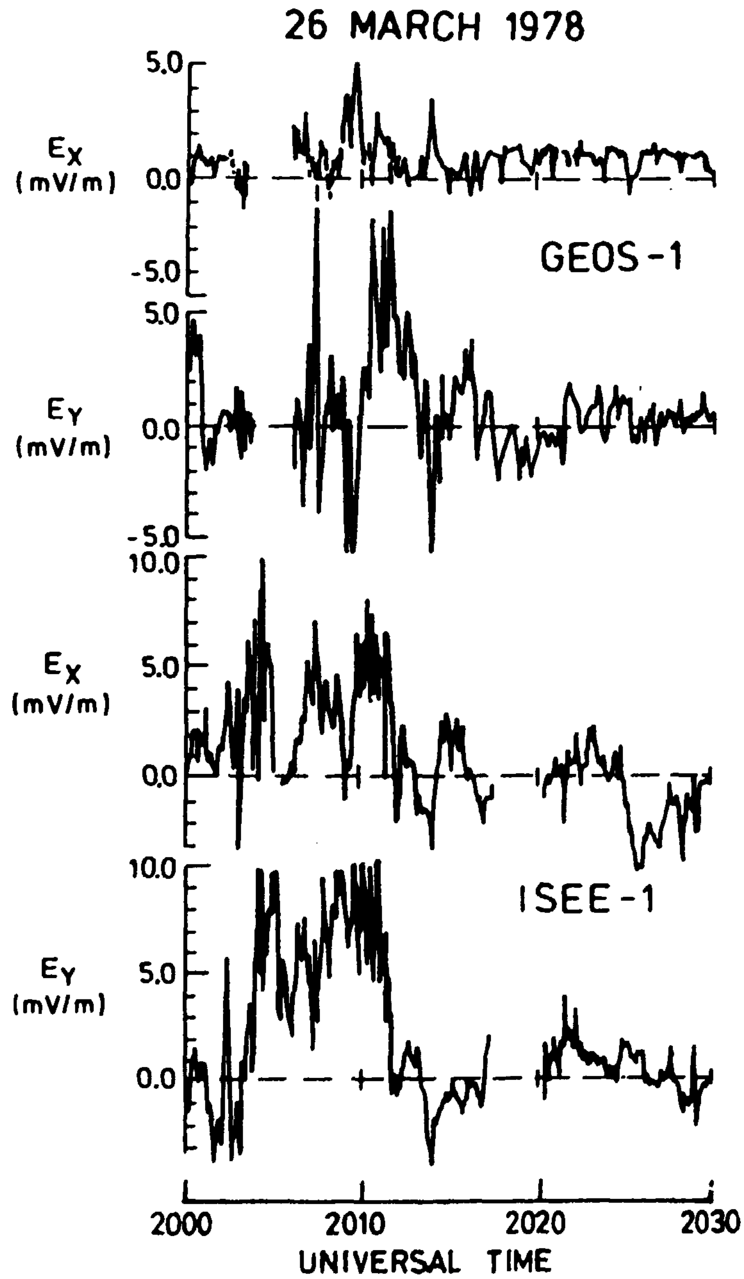

26 MARCH 1978
5.0
E_X
(mV/m)
0.0
GEOS-1
-5.0
5.0
E_Y
(mV/m)
0.0
-5.0
10.0
E_X
5.0
(mV/m)
0.0
10.0
ISEE-1
E_Y
5.0
(mV/m)
0.0
2000
2010
2020
2030
UNIVERSAL TIME

Fig. 9

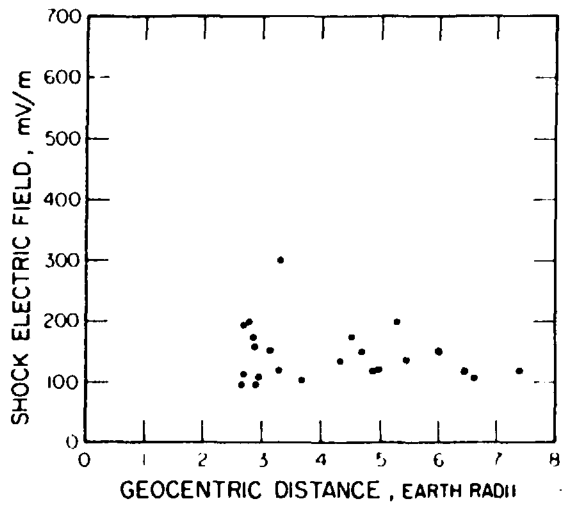
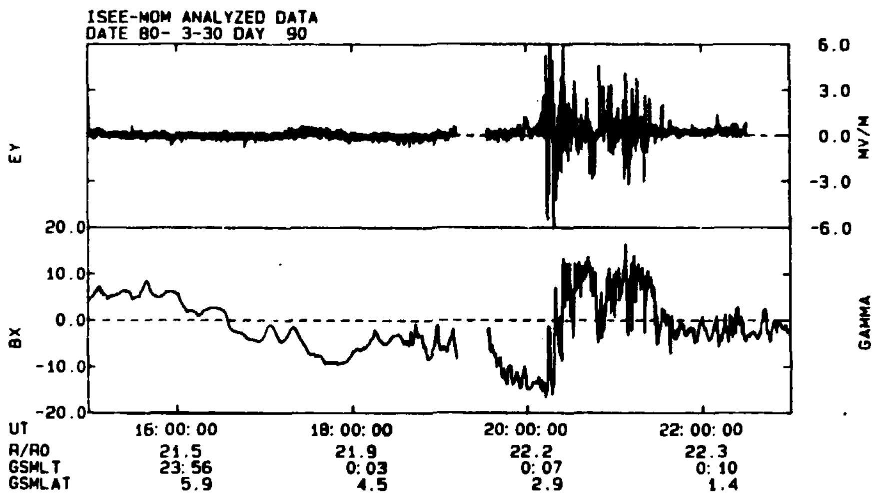

SHOCK ELECTRIC FIELD, mV/m
0
100
200
300
400
500
600
700
0
1
2
3
4
5
6
7
8
GEOCENTRIC DISTANCE, EARTH RADII

Fig. 10



ISEE-MOM ANALYZED DATA
DATE 80- 3-30 DAY 90
EY
MV/M
6.0
3.0
0.0
-3.0
-6.0
BX
GAMMA
20.0
10.0
0.0
-10.0
-20.0
UT
R/RO
GSMLT
GSMLAT
16:00:00
21.5
23:56
5.9
18:00:00
21.9
0:03
4.5
20:00:00
22.2
0:07
2.9
22:00:00
22.3
0:10
1.4

Fig. 11

SIGNATURES OF PLASMA VORTICES (3/2/78)

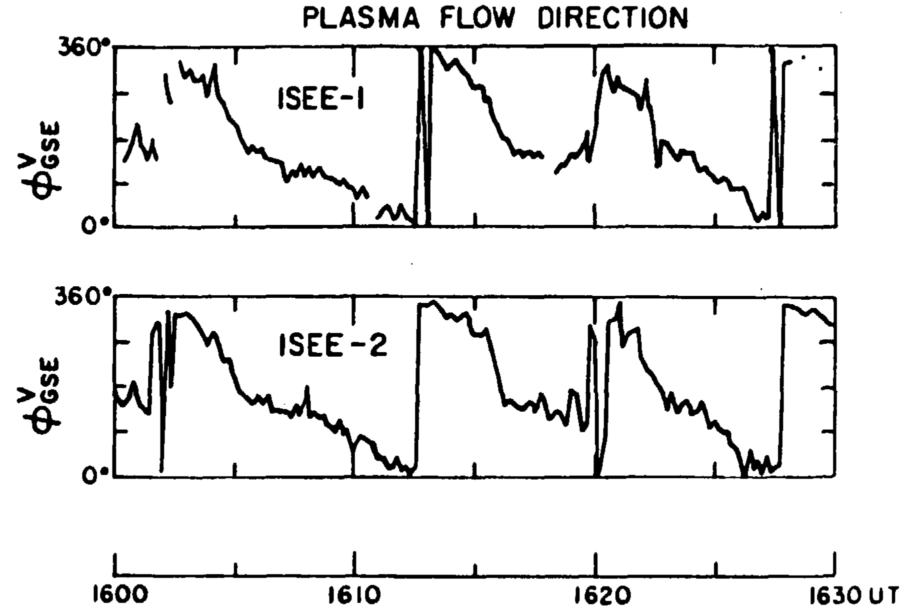


Fig. 12

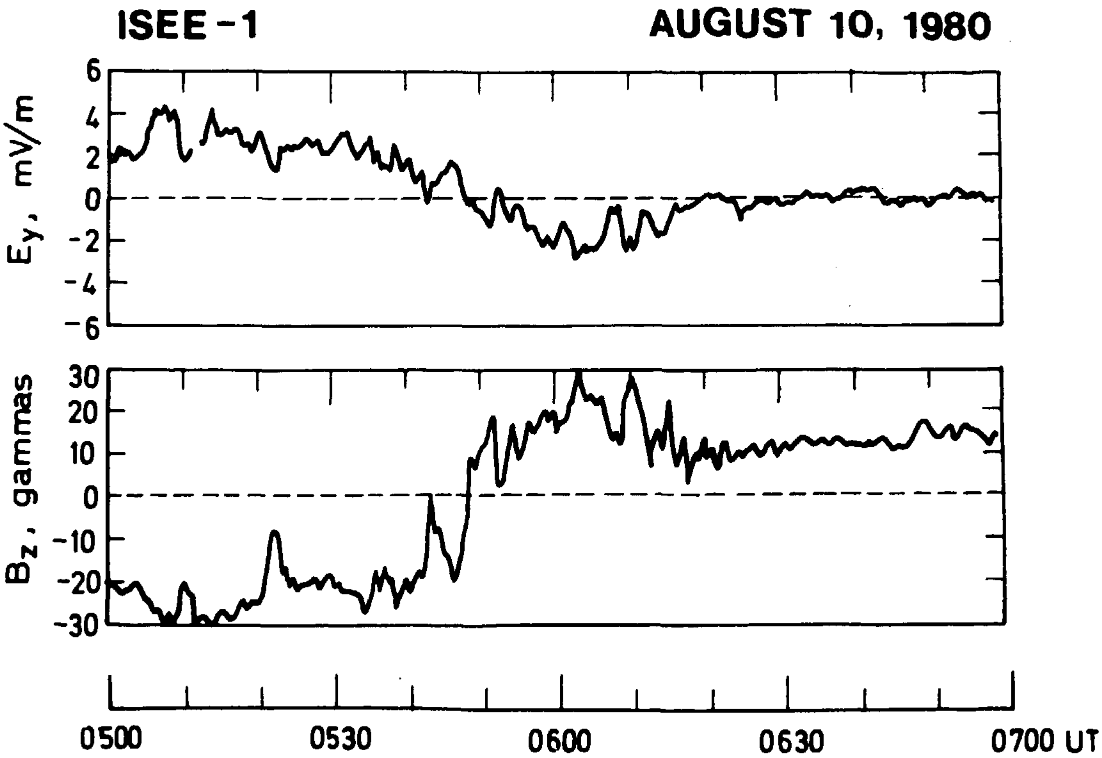

ISEE-1
AUGUST 10, 1980
6
4
2
0
-2
-4
-6
Ey, mV/m
30
20
10
0
-10
-20
-30
Bz, gammas
0500
0530
0600
0630
0700 UT

Fig. 13

DATE 1986-04-09 ORBIT 257 VIKING V1 DATA

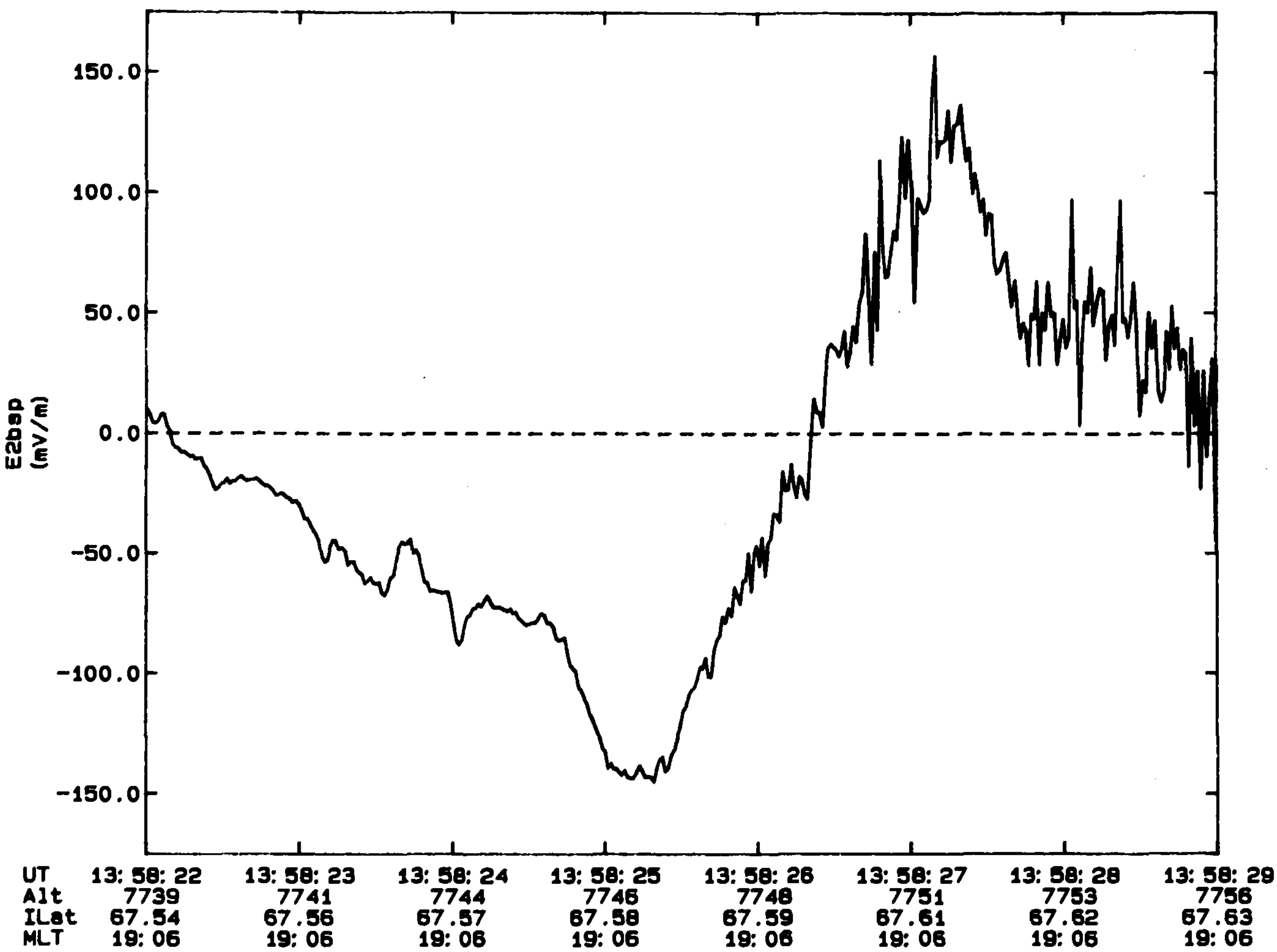
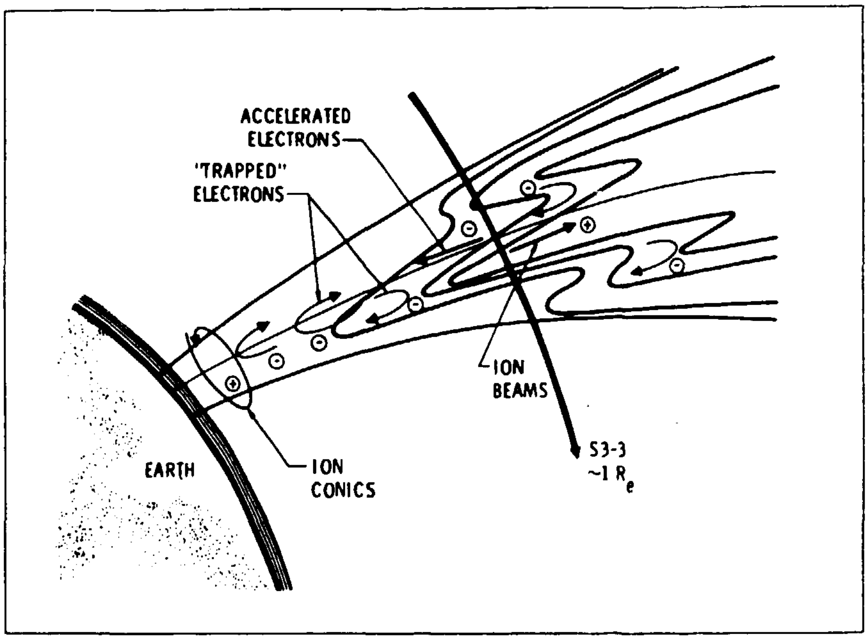


Fig.14



ACCELERATED
ELECTRONS
'TRAPPED"
ELECTRONS
ION
BEAMS
S3-3
~1 R e
EARTH
ION
CONICS

Fig. 15

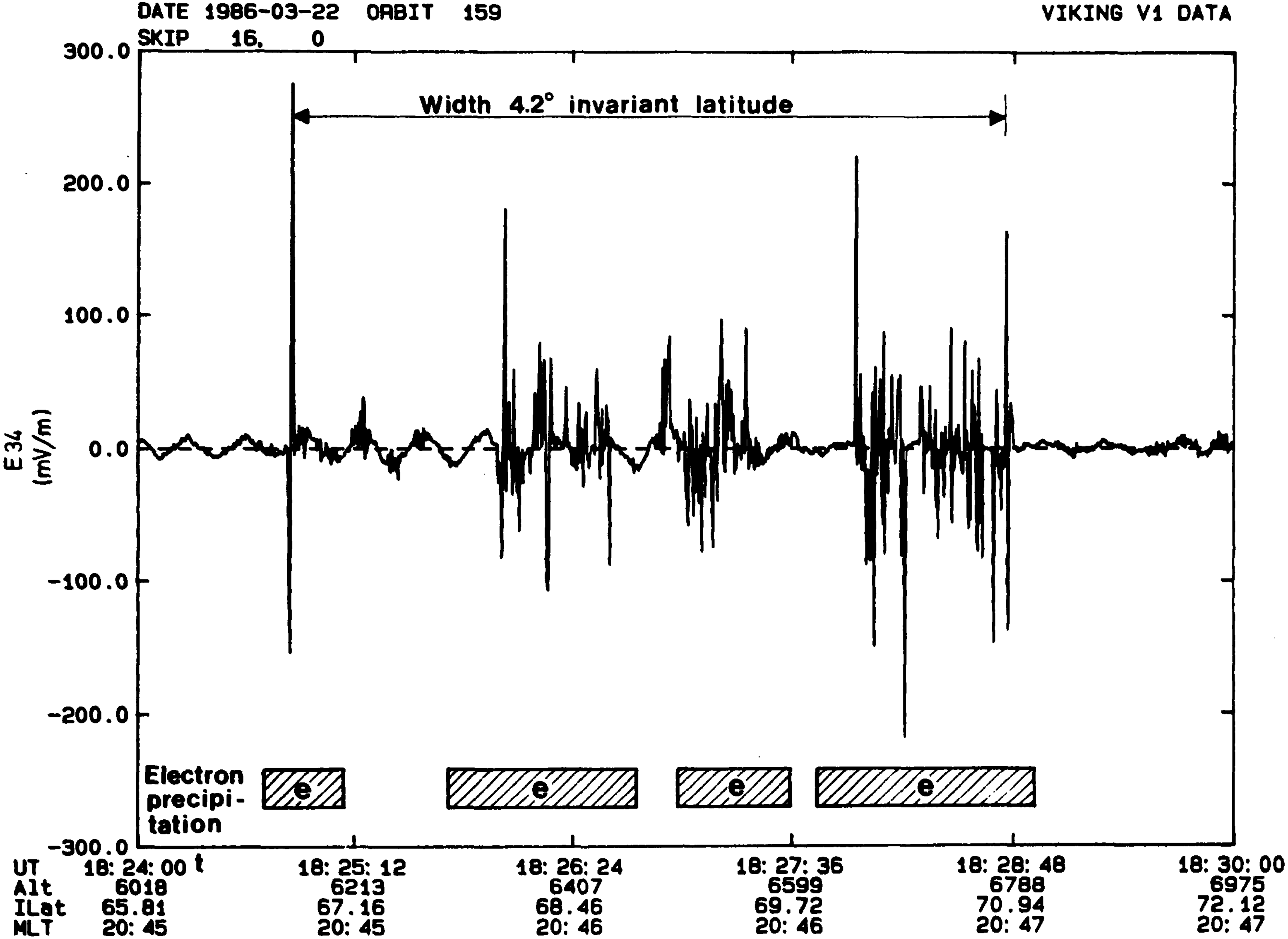

DATE 1986-03-22 ORBIT 159
SKIP 16. 0
VIKING V1 DATA
Width 4.2° invariant latitude
300.0
200.0
100.0
0.0
-100.0
-200.0
-300.0
E 34
(mV/m)
Electron precipi-tation
e
e
e
e
UT 18: 24: 00 t 18: 25: 12 18: 26: 24 18: 27: 36 18: 28: 48 18: 30: 00
Alt 6018 6213 6407 6599 6788 6975
ILat 65.81 67.16 68.46 69.72 70.94 72.12
MLT 20: 45 20: 45 20: 46 20: 46 20: 47 20: 47

Fig. 16

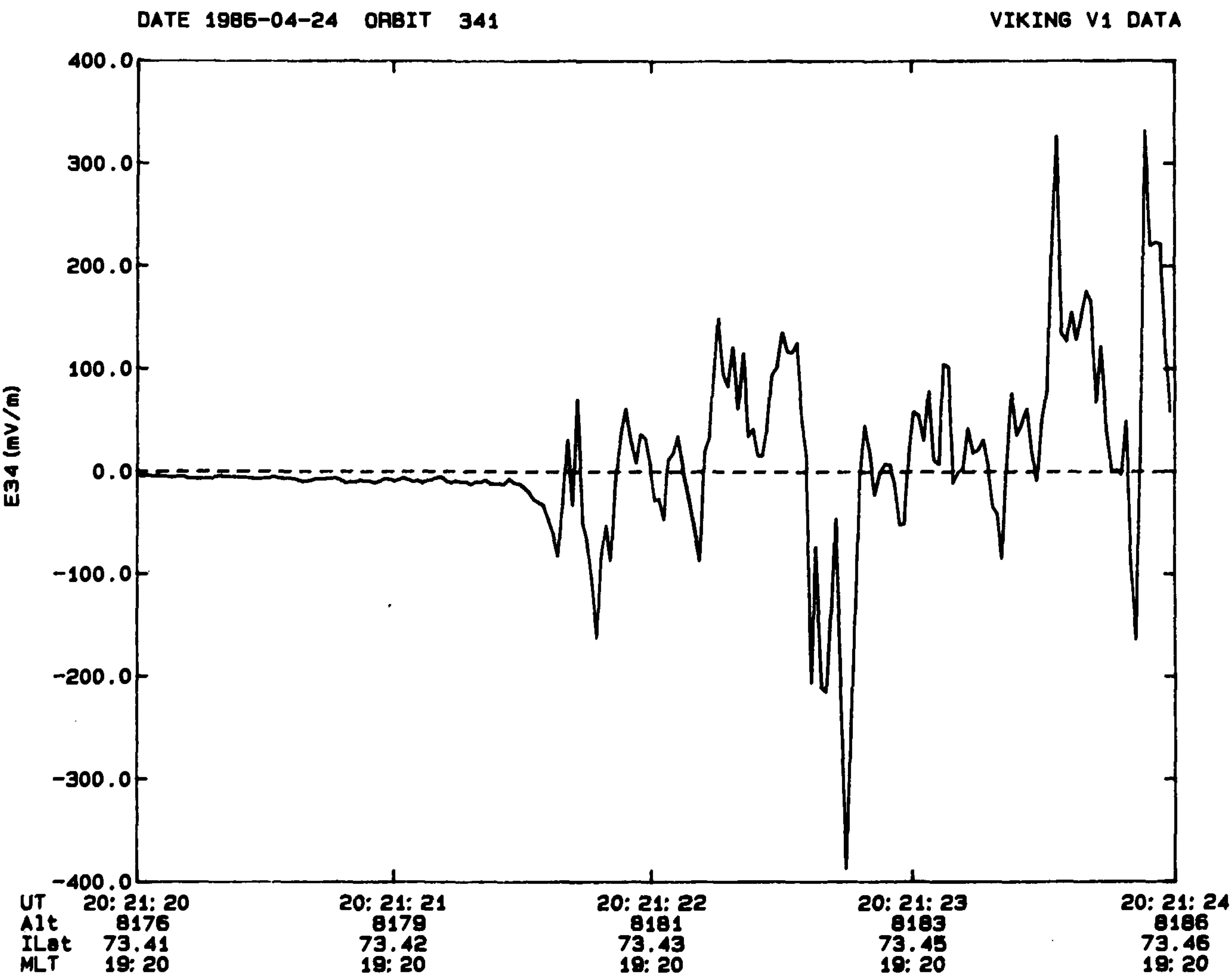

DATE 1986-04-24 ORBIT 341
VIKING V1 DATA
400.0
300.0
200.0
100.0
0.0
-100.0
-200.0
-300.0
-400.0
E34 (mV/m)
UT 20: 21: 20
20: 21: 21
20: 21: 22
20: 21: 23
20: 21: 24
Alt 8176
8179
8181
8183
8186
ILat 73.41
73.42
73.43
73.45
73.46
MLT 19: 20
19: 20
19: 20
19: 20
19: 20

Fig. 17

TRITA-EPP-89-06 ISSN 0348-75?9

The Royal Institute of Technology, Department of Plasma Physics
S-100 44 Stockholm, Sweden

ELECTRIC FIELDS IN THE MAGNETOSPHERE

C.-G. Fälthammar

December 1989, 40 pp., incl. illus., in English

The electric field plays an important role in the complex plasma system called the magnetosphere. In spite of this, direct measurements of this quantity are still scarce except in its lowest-altitude part, *i.e.*the ionosphere. The large scale ionospheric electric field has been determined from measurement on the ground and in low satellite orbit. For most of the magnetosphere, our concepts of the electric field have mostly been based on theoretical considerations and extrapolations of the ionospheric electric field.

Direct, *in situ*, electric field measurements in the outer parts of the magnetosphere have been made only relatively recently. A few satellite missions, most recently the Viking mission, have extended the direct empirical knowledge so as to include major parts of the magnetosphere.

These measurements have revealed a number of unexpected feature The actual electric field has been found to have unexpectedly strong space and time variations, which reflect the dynamic nature of the system. Examples are given of measured electric fields in the plasmasphere, the plasmasheet, the neutral sheet, the magnetotail, the flanks of the magnetosphere, the dayside magnetopause and the auroral acceleration region.

Keywords: Electric fields, Ionosphere, Magnetosphere