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ELECTRIC FIELDS IN THE MAGNETOSPHERE
A REVIEW

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ELECTRIC FIELDS IN THE MAGNETOSPHERE - A REVIEW

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Abstract

The satellites S3-3, GEOS-1, GEOS-2, ISEE-1 and Viking have extended direct measurements of electric fields to include the outer regions of the magnetosphere.

The measurements confirm some of the theoretically expected properties of the electric fields. More importantly, they also reveal unexpected features and a high degree of complexity and variability. The existence of a magnetospheric dawn-to-dusk electric field has been confirmed in an average sense. However, the actual field exhibits large spatial and temporal variations, including strong fields of inductive origin. At the magnetopause the average (dawn to dusk directed) tangential electric field component is typically obscured by irregular fluctuations of larger amplitude.

The magnetic-field aligned component of the electric field, which is of particular importance for ionosphere-magnetosphere coupling and for auroral acceleration is even now very difficult to measure directly. However, the data from electric field measurements provide further support for the conclusion, based on a variety of evidence, that a non-vanishing magnetic-field aligned electric field exists in the auroral acceleration region.

1. Introduction

Unlike most other physical parameters in the Earth's environment the electric field was not subject to direct measurement until quite late in the space age. The reason for this was twofold.

(1) According to prevailing theoretical models of the space plasma the electric field was a secondary parameter of little interest, and

(2) The electric field is technically very difficult to measure, at least at high altitudes, where the thinness of the plasma makes it very sensitive to disturbances.

The existence of a large-scale dawn to dusk electric field in the magnetosphere was foreseen already in Alfvén's (1955, 1958) theory of magnetic storms and auroras. Assuming, in addition to forced corotation of near-Earth plasma, a "viscous interaction" between the solar wind and the magnetosphere - assumed to have a closed magnetic topology - Axford and Hines (1961) deduced a qualitative convection pattern, which also implied a large-scale dawn-to-dusk electric field distribution immediately outside the corotation region. But unlike Alfvén's model its equipotentials were closed, implying no net dawn-to-dusk voltage. Dungey (1961) introduced the concept of a magnetosphere with a topologically open magnetic field due to interconnection of the terrestrial and interplanetary magnetic fields (cf. also Piddington, 1962, 1963 a,b). In terms of the magnetospheric electric field it was similar to that of Alfvén's model, and different from that of Axford and Hines. The implied predictions about the magnetospheric electric field have now been tested against direct measurements, and will be discussed below.

An early method of determining the magnetospheric electric field was provided by the study of ducted whistlers (Carpenter and Stone, 1967, Carpenter et al., 1972). As the method relies

on consequences of radial displacements of ducts, only the azimuthal electric field can be deduced. Furthermore, even that deduction is subject to error if the electric field is inductive (Block and Carpenter 1974), and we now know from direct measurements that strong induction fields do occur.

2. Earthbound deductions

The information derived from whistlers was in general agreement with both open and closed magnetosphere models. The differences between the models in terms of electric fields become important only beyond the reach of whistler-based deductions (cf. §§ 12 and 13).

From ground-based magnetometry, conclusions can be drawn about the distribution of electric potentials in the ionosphere. More recently the availability of powerful ground-based radars have allowed mapping of the ionospheric electric field. From the ionospheric electric field the magnetospheric field has been deduced by extrapolation.

Although such deductions involve errors, especially where the outermost parts of the magnetosphere are concerned, cf. §4, the main results were essentially in agreement with the results of whistler studies and with the major theories mentioned above.

However, the limited knowledge that could be inferred from the ground was not sufficient for distinguishing between different theoretical models of the magnetospheric field.

3. Near-Earth observations

With the advent of Earth satellites, direct electric field measurements became possible, although they were much fewer than e. g. magnetic measurements - and initially performed only in low orbit. From such measurements a considerably improved picture of the average ionospheric electric field emerged. However, since the field is variable and measurements were made

during single satellite passages spaced by more than an hour in time, it was still only possible to determine average, or typical, electric field distributions (different for different interplanetary conditions).

A complementary method of determining the average ionospheric electric fields is to use balloon-borne electric field measurements. The altitude variation of electric conductivity in the atmosphere is such that the large-scale (greater than about 100 km) horizontal electric field in the ionosphere maps down nearly without attenuation to a height of about 30 km, which can be reached by balloons. Balloon-borne measurements are complementary also in the sense that they provide continuous measurements (unlike the intermittent measurements by low altitude satellites).

Balloon-borne measurements of ionospheric electric fields and magnetospheric electric fields were used by Mozer and Serlin (1969) and Mozer and Manka (1971) to deduce the average magnetospheric convection pattern. Iversen et al (1984) and Tanskanen et al (1987) used balloon-borne electric field measurements as a complement to in situ data from the GEOS satellite for comprehensive studies of specific events.

As will be described below (§15), it is only very recently that, by a combination of satellite measurement and sophisticated electrodynamic modelling, it has become possible to obtain good knowledge of the "instantaneous" large-scale electric field distribution at a given time.

4. Mapping of ionospheric electric fields to the magnetosphere

The mapping of ionospheric electric fields to the magnetosphere or vice versa is difficult for at least three reasons.

(1) In spite of the fact that extensive satellite-borne magnetometer measurements have provided a rather good knowledge of typical magnetic field vectors in any given region, the knowledge is not sufficient for reliable determination of the shape

of a given high-latitude magnetic field line, i. e. of the magnetic mapping between the ionosphere and the outer magnetosphere. For a discussion and examples, see e. g. the review by Fälthammar (1985).

(2) The magnetic field lines are not everywhere electric equipotentials (cf. §6), and this limits the validity of mapping.

(3) Especially during the most interesting geophysical conditions, such as substorms, the time variation of the magnetic field is strong, and the global electric field is not a potential field (although in limited regions the electric field can still be approximated by an equipotential field.)

Referring to point (1) above we may note that quite sophisticated quantitative models of the geomagnetic field are now available, see for example Toffoletto and Hill (1986), Tsyganenko (1987) and references therein. Such models allow calculation of the average - or, more correctly, typical - values

of the magnetic field vector for given conditions. However, determination of actual magnetic conjugacy over large distance is much more uncertain since even small systematic errors in the model vector can integrate to substantial errors in the location where the field line ends up. Even as close as at the geosynchronous orbit, changes in the solar wind condition may change the mapping to the ionosphere by several degrees both in latitude and longitude (Greenwald, 1981). The uncertainty in magnetic conjugacy between the ionosphere and the distant magnetosphere is of course even greater at higher latitudes, especially near magnetic-field aligned current sheets as strikingly shown by Lui and Krimigis (1984).

Somewhat less uncertain than the actual conjugacy is the mapping factor, i.e. the ratio of separations between adjacent field lines in the magnetosphere and the ionosphere. An early discussion of the mapping factor was given by Mozer (1970). Data from GEOS and STARE have been used to obtain empirical mapping factors (Schmidt et al., 1985). An example of the result is given in Fig. 1.

The mapping of electric fields was also discussed by Mozer (1976), who used balloon flights to determine the ionospheric electric field and to use the result for deducing the magnetospheric field by mapping (Mozer and Torbert, 1980).

5. Inference from measurements of plasma and energetic-particles

Long before electric field measurements were performed in the outer magnetosphere, traditional measurements of e.g. plasma density and energetic-particle fluxes were performed there. Some of those results could be used to infer some properties of the magnetospheric field. Thus, plasma measurements improved the knowledge of the location and shape of the plasmopause. To the extent that the plasmopause is at least approximately coincident with the boundary between open and closed electric equipotentials, this also improved the knowledge of the electric field.

Analyzing the arrival-time dispersion of energetic particle clouds impulsively injected into closed drift orbits (McIlwain, 1972) derived average configurations of the magnetospheric electric field. Recently an improved, K_p -dependent, model has been developed (McIlwain, 1986). 3. It shows the same general features as discussed above (corotation region and general dawn-to-dusk directed electric field).

6. High altitude observations

Among the scientific achievements of the S3-3 satellite was the first measurement of electric fields at high altitude above the high latitude ionosphere. This led to important discoveries. One was that of very strong transverse electric fields (originally termed "electrostatic shocks") with field strengths of hundreds of mV/m extending over distances of the order of a few km. The phenomenon has later been observed also with Dynamics Explorer 2 (Maynard et al., 1982), ISEE-1 (§9) and Viking (§14). As it is well known from low altitude measurements that

such fields are not present in the ionosphere, it is directly and conclusively proved that the mapping of electric potential magnetic field lines does not hold. This imperfect mapping implies that at some intermediate altitude there must exist either a magnetic-field aligned electric field (such that $\text{curl } E_{\parallel} \neq 0$, even though $\text{curl } \underline{E} \approx 0$) or a time varying magnetic field, capable of causing sufficiently large electric induction fields, (e. g. associated with strong Alfvén waves).

Although strong Alfvén waves may play a role in the auroral process, as suggested by Haerendel (1983), we know from the Viking results (cf §14), that the electrostatic shocks are not associated with magnetic field perturbations of anywhere near the magnitude expected for Alfvén waves.

Alreday from the S3-3 results it could be concluded that the electrostatic shocks were not caused by induction, and that therefore magnetic-field aligned electric fields must exist (Mozier et al., 1980). This is because remote sensing of electrostatic shock-associated VLF emissions (observed as "saucers") allow estimating a lower limit to the life of the shocks. This turns out to be so long that the time derivative of the magnetic field that would be required would lead to unreasonable magnetic field changes during the life of the electrostatic shock (Mozier et al., 1980). The conclusion has been more directly verified by the Viking satellite, which showed that the magnetic field variations, if any, were orders of magnitude too small to account for the electrostatic shocks by induction.

Another S3-3 discovery was that of numerous small-scale electric field structures, "electric double-layers" (Temerin et al., 1982; Mozier and Temerin, 1983), illustrated in Fig. 2. Although each of them has only a small (fraction of a Volt) potential drop, they may together support magnetic field aligned electric fields with kilovolt potential drops, which are sufficient to play a role in auroral acceleration. Both of these discoveries have afterwards been extensively confirmed,

especially by the Swedish satellite Viking (Block et al., 1987 a,b; Fälthammar et al., 1987; Block, 1987, 1988; Koskinen et al., 1987, Boström et al., 1988).

Comparisons between high and low altitude electric fields measured by S3-3 were made by Mozer and Torbert (1980). They revealed a characteristic difference implying a lack of mapping. From this it was estimated that the potential drop along magnetic field lines was of the order of a few kV. From comparisons between Dynamic Explorer 1 and 2 Weimer et al. (1985) concluded that the electric field distributions at altitudes 900 km and 4500 km were consistent in terms of large scale features but also that the small scale features (less than 100 km) were stronger at the higher altitude. In this case, too, potential drops of the order of kV were inferred. They were also correlated with the density of magnetic-field aligned currents.

The first satellite to measure electric fields at distances of many Earth radii in the equatorial regions was GEOS-1, later followed by GEOS-2. The international satellite ISEE-1 for the first time extended direct electric field measurements throughout most magnetospheric regions inside 22 Earth radii and also to the magnetopause, the magnetosheath, bow shock and solar wind. Results of these IMS satellites will be discussed in subsequent sections. A brief summary is found in a review by Fälthammar et al. (1984). Recently a major further step has been taken with the post-IMS satellite Viking, which has made comprehensive measurements up to 13 527 km in the auroral acceleration region. These results, too, will be outlined below, where we will summarize the character of the magnetospheric electric fields, as we now know them.

7. Overall properties of the magnetospheric fields as determined by direct measurements

Not surprisingly, the direct measurements of the magnetospheric electric field have confirmed some of the broad features that

had been inferred from groundbased and low orbit observations, such as the corotational electric field in the plasmasphere and the existence, in an average sense, of a dawn-to-dusk electric field outside that region.

However, the local and instantaneous properties can be very different from the average picture. For example, the dawn-to-dusk electric field has proved to be characterized more by its variations than by its average value.

Some questions of crucial importance to magnetospheric physics have been answered, such as whether the magnetopause is an equipotential or not, and to what extent the outermost magnetosphere contains a dusk-to-dawn electric field as predicted from the hypothesis of "viscous interaction".

The following sections (§§8-15) will describe some characteristics of the electric fields observed in the various regions of the magnetosphere.

In many of these regions it has also been possible to measure the electric field components of ULF waves, which have previously only been known only in terms of their magnetic fields. This will be briefly discussed in §16.

8. The plasmasphere

The plasmasphere is populated by a collision-dominated plasma for which the Generalized Ohms law can be expected to hold. It is therefore, electrodynamically, the least complicated part of the magnetosphere. At least in the inner parts of this region one would expect a corotational electric field simply mapped from the corresponding areas of the ionosphere. The measurements with GEOS 1 and 2, and ISEE-1 have confirmed this but also shown interesting deviations (Maynard et al., 1983; Pedersen et al. 1984). Thus, the average quiet-time electric fields largely agrees with what has been expected from whistler results and theoretical considerations. However, the

instantaneous electric field is highly variable and shows considerable deviations from simple corotation. An example of the plasmaspheric electric field is shown in Fig. 3. Inside 3.3 Earth radii there is a very good agreement with the expected corotational electric field, but further out considerable deviations from corotation are found. Systematic study and interpretation of such deviations remains to be made.

Especially during disturbed conditions large deviations from corotation are observed near the plasmopause, (Maynard et al., 1983). Just inside the dusk side of the plasmopause electric fields many times stronger than the corotational 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 plasmopause. The field strength projected to ionospheric level exceeded 100 mV/m, and the event was accompanied by significant penetration of the convection electric field inside the plasmopause (Maynard et al., 1980). 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. e.g. Fahleson et al., 1971)

The plasmasheet

Unlike a largely homogeneous and steady dawn-to-dusk electric field, the actual electric field in the plasmasheet, has proved to be extremely variable not only in time but also in space. During geomagnetically quiet times the electric field is too weak to be measured with the double probes flown so far, i.e. less than a few tenths of mV/m. Finite small values (0.1-0.3 mV/m) have, however, been measured with the electron beam technique on the GEOS spacecraft (Baumjohann et al., 1985).

During active times, and especially during the substorm expansive phase, the electric fields are much stronger, but very variable both in time and space (cf. e.g. Aggson et al., 1983a; Pedersen et al., 1985). In this context, induction

electric fields are important, which means that- strictly speaking - there does not even exist an electric potential on the global scale. (During active times there is also a considerable wave activity, which will be discussed in §16.) An example of electric fields measured in the plasmasheet is given in Fig. 4.

Particularly strong electric fields are observed near the plasmasheet boundary. Field strengths up to several tens of mV/m have been recorded. As shown by Pedersen et al. (1985) these electric fields are inductive in nature (in agreement with the predictions by Heikkila et al. 1979).

During the time when both GEOS 2 and ISEE-1 were operative two-point measurements of magnetospheric electric fields were obtained. One of the interesting results of this was the observation of a time delay between electric field pulses observed at the two satellites (Fig. 5). The direction of propagation was usually toward the Earth, and the velocity was of the order of the average Alfvén velocity in the intervening region.

At the poleward boundary of the plasmasheet even stronger electric fields were occasionally seen with ISEE. These have been interpreted as high altitude cases of the above mentioned "electrostatic shocks" that are abundant in S3-3 and Viking data. It is an interesting fact that the peak electric field strength is essentially independent of altitude in the range 2.5 to 7 Earth radii (rather than decreasing with altitude as mapping along magnetic field lines would require).

10. The neutral sheet

In the neutral sheet, too, the electric field is very different during quiet and active times. In the former case the electric field is typically less than 0.5 mV/m. During active times, however, the neutral-sheet electric field is very irregular and quite strong. The dominating wave mode has been identified as lower hybrid by Cattell and Mozer (1986). The authors suggest

that the observed wave fields are strong enough to provide a substantial anomalous resistivity.

11. The magnetotail

In the central tail lobes the plasma density is usually too low for satisfactory operation of the double probe. However, in other regions of the tail measurements have been possible. Conclusions about the electric field have also been drawn from plasma flow detected through anisotropies in measured particle fluxes. One result of the latter kind, which has also been confirmed by comparisons with electric field data, is the occurrence of velocity fields with a non-vanishing vorticity, (originally referred to as "vortices").

12. The general convection field

As already mentioned in §7 the dawn-to-dusk electric field expected from ground based and low altitude observations exists in an average sense, while the instantaneous field is extremely variable.

In the Axford and Hines (1961) model, the sum of the morning and evening side potentials of the dusk-to-dawn electric fields should be equal to that of the dawn-to-dusk electric field further in near the flanks of the magnetosphere. From a number of ISEE-1 passages, Mozer (1984) has observed a dusk-to-dawn directed electric field near the flanks of the magnetosphere. This is a field of the kind envisaged in "viscous interaction" models such as that of Axford and Hines (1961). However, the dusk-to-dawn electric field reported by Mozer has a potential that is only a small fraction of that required by the Axford and Hines model. Objections raised by Heikkila (1986) concerning the precise value of the dusk-to-dawn potential do not change the main conclusion that "viscous interaction" typically accounts for a rather small part of the total magnetospheric electric field.

The conclusion that viscous interaction is of minor importance is further supported by GEOS-2 observations by Baumjohann and Haerendel (1985), which have shown that the (3 hour averaged) dayside convection electric field at 6.6 Earth radii does not correlate with the solar wind momentum flux. On the other hand the authors find a substantial correlation between the convection electric field and the southward component of the interplanetary magnetic field.

13. The magnetopause

A key issue in magnetospheric physics has been whether the magnetopause is an electric equipotential (Heikkila, 1975), as in closed magnetospheric models or has a finite dawn-to-dusk directed tangential component of the electric field, as in models with open magnetic topology.

One of the surprising results of the direct electric field measurements 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 electric field stands out fairly clearly (Mozer et al. 1979), but that is exceptional. However, from a statistical study of many magnetopause passages, Lindqvist and Mozer (private communication) have confirmed a non-vanishing dawn-to-dusk directed tangential electric field with a strength of the order of a mV/m and positively correlated with the strength of the southward interplanetary magnetic field. This feature is expected from open models of the magnetosphere. It is also in agreement with the observations of Baumjohann and Haerendel (1985) referred to in §12. Occasional large electric fields (10 mV/m or more) have been observed at rotational magnetopause discontinuities by Aggson et al. (1983b).

The unexpected large fluctuations of the magnetopause electric field, discovered with ISEE-1 are probably more important than the d c electric field that has been the focus of prevailing theoretical models. The measured electric fields imply that the

physics of the magnetopause is far more complex than envisaged in current "reconnection" models. The fluctuations are probably important for the penetration of plasma into the magnetosphere as suggested by Lemaire (1977, 1979, 1985, Lemaire et al., 1979; Lemaire and Kowalkowski, 1981; Lemaire and Roth, 1981;), Heikkila (1982 a,b) and Lundin (1984).

14. The auroral acceleration region

Probably the most interesting electric field observations of all are those made in the auroral acceleration region.

The first electric field measurements in this region were made with the S3-3 satellite. It led to two major discoveries: (1) "electrostatic shocks" and (2) multiple electric double layers.

The "electrostatic shocks" are regions with very strong - hundreds of mV/m - electric fields directed predominantly transverse to the magnetic field and extended over a few km (with potentials of a few kV). The discovery was made with S3-3 (Mozar et al., 1977, 1980, 1985) in the altitude range up to the S3-3 apogee of 8000 km. Occasional examples have been observed also in the ISEE-1 orbit (cf §10 and Fig. 8). The most extensive observations of the phenomenon have been made with the Swedish satellite Viking, which extended the measurement of electric fields to 13 527 km. Viking revealed an even more complex fine structure than that known from S3-3 (Block et al., 1987a,b; Fälthammar et al., 1987). An example of an electric field structure of the "electrostatic shock" type observed with Viking is shown in Fig. 6.

A typical feature of 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. 7. The transition from quiet several mV/m electric fields at subauroral latitudes to the auroral oval type fields is often extremely sharp. It can occur in a

fraction of a second, corresponding to less than a km of satellite trajectory.

The rapid variations in the transverse electric field are electrostatic in the sense that any corresponding variations in the magnetic field have a ratio to the electric field variations that is orders of magnitude less than what is typical of Alfvén waves. Although 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 observable. A plausible interpretation is that the observed strong and irregular transverse electric fields ("electrostatic shocks") are associated with the magnetic-field aligned portions of electric equipotentials associated with multiple electric double layers as illustrated in Fig. 8.

There are also several additional indications in the Viking data that in the auroral acceleration region there exist magnetic-field aligned electric fields, although they are not easily accessible to direct measurements (Block et al , 1987 a,b; Block and Fälthammar, 1988).

15. Global electrodynamics of the ionosphere-magnetosphere system

In situ measurements in the magnetosphere have, by necessity, a limited time and space coverage. Measurements are taken along satellite orbits that are traversed at intervals of more than an hour for low orbits and many hours for high orbits. However, by combining (1) in situ measurements with (2) remote sensing information such as the Viking UV pictures of the whole auroral oval and (3) a quantitative mathematical model of the electrodynamics of the auroral ionosphere, rather detailed information can be obtained of the "instantaneous" distribution of auroral electric fields and currents.

Global models of the ionospheric electric field, currents and conductivities have been developed by several authors. The

input quantities used are typically the ionospheric conductivity combined with either the ionospheric potential or the ionospheric magnetic-field aligned current (Nisbet et al., 1978; Kamide and Matsushita, 1979; Bleuler et al., 1982; Marklund et al., 1986). By combining results of ground based observations with data simultaneously obtained from spacecraft, schematic convection patterns have been obtained both for the nightside high-latitude ionosphere (Heelis et al., 1983) and for the dayside ionosphere (Marklund et al., 1986). Extending this approach to global numerical simulations can be very effective in clarifying the instantaneous state of the ionosphere-magnetosphere system. Particularly useful in this context are the results of remote sensing of the global auroral luminosity distribution from DE 1, Hilat and Viking. This is because the distribution of ionospheric conductivity is crucial for accurate modelling (Reiff, 1984), and the UV images of the aurora can be used to give a rather good estimate of the instantaneous global conductivity distribution and also rough estimates of the global distribution of upward magnetic-field aligned currents.

Kamide et al. (1986) combined DE 1 pictures (to estimate conductivity distributions) and ground based magnetometer data to calculate global distributions of electric fields, electric currents and Joule dissipation.

The most promising technique so far has been developed in a series of papers by Marklund and Blomberg (Marklund et al., 1987 a,b, 1988; Blomberg and Marklund, 1988 a,b). It makes use of (1) auroral UV-images from satellites, combined with (2) in situ observations of electric fields, precipitating particles and magnetic fields (from which the in situ magnetic-field aligned currents can be determined) as well as (3) ground based data relevant to these parameters.

Comparison of the high-altitude electric field measured with Viking and the ionospheric electric potential distribution calculated under the assumption of equipotential magnetic field

lines reveals expected deviations of the right sign and magnitude on those field lines where the presence of accelerated particles indicate parallel electric fields (Marklund et al., 1988).

Fig. 9 shows an example of the "instantaneous" global electric potential in the ionosphere as calculated from the Marklund-Blomberg model and the electric field measured in situ with Viking and projected down to the ionosphere. (To facilitate comparison the Viking electric field is represented by means of the ExB vectors, which should be tangent to the electric equipotentials.)

The instantaneous global electric potential pattern calculated by Marklund and Blomberg show - as it should - a general but not detailed agreement with average patterns calculated for the same geophysical conditions. An example is shown in Fig. 10. The instantaneous pattern calculated by Marklund and Blomberg has also been projected to the equatorial plane and compared to the average plasmapause. The instantaneous demarcation line between open and closed equipotentials of the instantaneous potential distribution shows, as it should, a general but not detailed agreement with the average plasmapause.

16. Electric fields of ULF waves

From ground based and satellite borne magnetometer measurements it has long been known that a variety of ULF pulsations occur in the ionosphere-magnetosphere system. The advent of direct electric field measurements in the magnetosphere represents an important step forward by allowing both the electric and magnetic components of such waves have been measured. This means that the wave mode involved can be determined much more reliably. Much work still remains to be done with the data already collected. Only a couple of interesting results will be mentioned here.

In the auroral acceleration region the Viking satellite often encountered very low plasma densities, corresponding to Alfvén velocities sometimes well above 10 000 km/s. This means that the ratio of electric to magnetic fields in an Alfvén wave is extremely high. As a result, the Viking electric field experiment was capable of measuring the electric fields of ULF waves which were so weak that their magnetic fields could not be detected at all with the magnetometer. Thus a whole new category of waves, previously unobservable, became accessible for investigation. An example is shown in Fig. 11.

Fig. 12 shows an example of a standing Alfvén wave observed with the Viking satellite. The small ratio of electric to magnetic fields in this case reflects the fact that the wavelength of this particular wave was much larger than Viking's altitude above the wave's ionospheric node.

From analysis of the phase relations between the electric and magnetic vectors in ULF waves it has been concluded that they are responsible for a substantial transport of energy between the magnetosphere and the ionosphere (Potemra, private communication).

17. Outstanding questions

The Earth's magnetosphere still poses a number of unsolved problems that involve electric fields in a fundamental way.

The way in which plasma enters the magnetosphere, both from the solar wind and from the ionosphere is still far from fully understood. The direct measurements so far have revealed important facts relevant to this problem. For instance, they have shown that the widely used reconnection models are far too idealized to describe the actual conditions at the magnetopause, where large fluctuating electric fields dominate over the small average field. More direct measurements of the actual electric field are needed to solve the problem of plasma entry.

The Earth's own ionosphere is an important source of magnetospheric plasma. The expulsion of ionospheric plasma is the result of complex interactions between the ionosphere and the magnetosphere. In these interactions electric fields, including magnetic-field aligned electric fields, seem to play an important role.

The electrodynamic coupling between ionospheric and magnetospheric regions is not known well enough. This remains an important obstacle, e. g. to the study of the substorm process.

The physics of the auroral acceleration region still holds a number of unanswered questions. They concern, for example, the existence, distribution and other properties of magnetic-field aligned electric fields, and their role in auroral particle acceleration. These are questions that are also relevant to the understanding of cosmical plasmas in general, which are known to have a remarkable capability of energizing charged particles.

The contrast between the comparatively regular electric fields in the ionosphere and the highly time and space dependent electric fields in the magnetosphere is puzzling. It reflects our limited understanding of the electrodynamic coupling between these regions. Substantial improvement of this understanding is necessary before we can correctly describe the physics of the Earth's magnetosphere. Such understanding is also essential in order to draw conclusions about physical processes in more distant cosmical plasmas that are inaccessible to in situ observations (Alfvén and Fälthammar, 1963; Fälthammar et al., 1978; Alfvén, 1981; Fälthammar, 1988)

18. 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 much still

remains to be done before this parameter is as well known as its importance justifies.

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Fig. 1. North-South (H_N) and East-West (H_E) geomagnetic mapping factors derived from comparisons between GEOS-2 and STARE data (Schmidt *et al*, 1985). Also shown are the early mapping factors H_{NM} and H_{EM} derived by Mozer (1970), H^1_{NM} and H^1_{EM} derived by Mozer and Lucht (1974) and one pair of values (dots denoted N and E) adapted from data provided from Haerendel.

Fig. 2. Multiple weak electric double layers observed with the S3-3 satellite (Mozer and Temerin 1983).

Fig. 3. Magnitude and direction of GEOS-1 spin plane component of the electric field for an inbound pass through the plasmashere (Pedersen et al., 1984). Curve (1) is a model field representing perfect corotation. Curve (2) is a model field without any corotation.

Fig. 4. Example of electric field measured in the plasma sheet (Pedersen et al., 1984).

Fig. 5. Electric field pulse observed both at ISEE-1 and GEOS-1 (Pedersen *et al.*, 1984).

Fig. 6. Close-up of an electrostatic shock observed with the Viking-satellite (Fälthammar et al., 1987). The structure of the double electric field spike is shown with high enough time resolution to show its structure. Electric fields with a strength of 150 mV/m are directed inward from both sides.

Fig. 7. Electric field signal (in the frame of the spinning satellite) during a nightside auroral oval crossing by Viking, showing correlation between regions of spiky electric fields and regions of electron precipitation (Fälthammar *et al.*, 1987). The regular sinusoidal variations at the satellite spin frequency reflect steady sub-auroral electric fields, whereas strong and irregular electric fields prevail above the auroral oval.

Fig. 8. Suggested interpretation of the irregular transverse electric fields observed on Viking in terms of equipotentials associated with multiple electric double layers (Block, 1988).

Lower left: schematic picture of potential variation along a magnetic field line with small double layers and solitons.

Upper right: electric field perpendicular to the magnetic field ($E_{\perp}$) along the satellite orbit obtained by projecting the magnetic-field-aligned potential along U-shaped equipotential surfaces.

Fig. 9. Comparison of "instantaneous" global ionospheric potential as calculated with the Marklund-Blomberg model and the *in situ* electric field measurements at Viking (Marklund *et al.*, 1988). For convenience of comparison, the Viking electric field, projected down to the ionosphere, is represented by $E \times B$ -vectors, which should be tangential to the equipotentials. The equipotentials are given in steps of 5 kV.

IONOSPHERE

MAGNETOSPHERE Equatorial plane

Fig. 10. Comparison between "instantaneous" and average potential distributions (Marklund, private communication).

- a) Instantaneous ionospheric electric potential pattern calculated with the Marklund-Blomberg model.
 - b) Average potential pattern according to Heppner and Maynard (1987) for the same conditions ($IMF B_y > 0$, $3 \leq K_p \leq 4$).
 - c) The same pattern projected to the equatorial plane.
- Also shown, for comparison, is the average plasmopause (heavy line) as deduced from Whistler data (Carpenter 1966).

Fig. 11. Electric field of ULF wave too weak to be observed magnetically (Fälthammar *et al.*, 1987). The upper panel shows the electric field in the frame of the spinning satellite, where the ULF field is superposed on the spin-frequency signal due to the d c electric field. The lower panel shows the despun electric field component in the satellite's spin plane and transverse to the magnetic field.

Fig.12. Electric and magnetic fields of a 2.5 min damped ULF oscillation observed with the Viking satellite (Block et al., 1987a). The upper panel shows the electric field component, E_2 (approximately along the satellite orbit), and the lower panel the magnetic field component B_3 (transverse to E_2 and approximately transverse to the average magnetic field).

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ELECTRIC FIELDS IN THE MAGNETOSPHERE - A REVIEW

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The satellites S3-3, GEOS-1, GEOS-2, ISEE-1 and Viking have extended direct measurements of electric fields to include the outer regions of the magnetosphere.

The measurements confirm some of the theoretically expected properties of the electric fields. More importantly, they also reveal unexpected features and a high degree of complexity and variability. The existence of a magnetospheric dawn-to-dusk electric field has been confirmed in an average sense. However, the actual field exhibits large spatial and temporal variations, including strong fields of inductive origin. At the magnetopause the average (dawn to dusk directed) tangential electric field component is typically obscured by irregular fluctuations of larger amplitude.

The magnetic-field aligned component of the electric field, which is of particular importance for ionosphere-magnetosphere coupling and for auroral acceleration is even now very difficult to measure directly. However, the data from electric field measurements provide further support for the conclusion, based on a variety of evidence, that a non-vanishing magnetic-field aligned electric field exists in the auroral acceleration region.

Keywords: Electric fields, Magnetosphere, S3-3, GEOS, ISEE