MAGNETOSPHERE-IONOSPHERE INTERACTIONS - NEAR EARTH MANIFESTATIONS OF THE PLASMA UNIVERSE

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Abstract

As the universe consists almost entirely of plasma, the understanding of astrophysical phenomena must depend critically on our understanding of how matter behaves in the plasma state. *In situ* observations in the near Earth cosmical plasma offer an excellent opportunity of gaining such understanding. The near Earth cosmical plasma not only covers vast ranges of density and temperature, but is the site of a rich variety of complex plasma physical processes which are activated as a result of the interactions between the magnetosphere and the ionosphere.

The geomagnetic field connects the ionosphere, tied by friction to the Earth, and the magnetosphere, dynamically coupled to the solar wind. This causes an exchange of energy and momentum between the two regions. The exchange is executed by magnetic-field-aligned electric currents, the so-called Birkeland currents. Both directly and indirectly (through instabilities and particle acceleration) these also lead to an exchange of plasma, which is selective and therefore causes chemical separation. Another essential aspect of the coupling is the role of electric fields, especially magnetic field aligned ("parallel") electric fields, which have important consequences both for the dynamics of the coupling and, especially, for energization of charged particles.

1. INTRODUCTION

Ionized matter - plasma - is the overwhelmingly dominating constituent of the universe as a whole. Matter in the plasma state is characterized by a complexity that vastly exceeds that exhibited in the solid, liquid and gaseous states. Correspondingly, the understanding of the physical, and especially the electrodynamical, properties of the plasma are still far from well understood.

These properties are still subject to basic research, and many fundamental questions remain to be answered. However, important progress has been made recently as a result of experiments in the <u>laboratory</u> and in those regions of <u>space</u> accessible to in situ observations and experimentation.

While it is universally acknowledged that our universe is a plasma universe, it seems to be far from fully realized that the physical understanding of this universe depends critically on our understanding of matter in the plasma state, In fact, the recent progress in plasma physics should provide a much improved foundation for understanding astrophysical processes in the universe of the present - as well as cosmogonic processes of the past. So far the increasing insight into the behaviour of matter in the plasma state has not been widely applied to astrophysics. To make full use of this insight should be a very important step toward a better understanding of our plasma universe.

A brief look at the evolution of plasma physics is useful in establishing an appropriate perspective.

Early plasma experiments were limited essentially to cool and/or weakly ionized plasmas. They formed the limited empirical basis on which the <u>classical plasma theory</u> was built. This theory was developed into a high degree of mathematical sophistication and was believed to have general validity. One of the predictions based on it was that magnetic confinement of plasma should be rather easy, and thermonuclear fusion possible within 15 years.

When the thermonuclear effort made it possible to produce and study hot and higly ionized plasma in the laboratory, it was found that the plasma exhibited many kinds of unpredicted, "anomalous" behaviour. The "thermonuclear crisis" that resulted led to the start of a new epoch in thermonuclear research, characterized by a close interplay between experimental and theoretical research. This has led to impressive progress in solving plasma physical problems that are vastly more complex than envisaged by classical plasma theory.

Similarly, in space research it was widely believed that the cosmical plasma would have negligible resistivity, as predicted by classical formulas, and behave essentially as an ideal MHD medium. If so, the electric field would be a secondary parameter of little importance, and magnetic-field-aligned ("parallel") electric fields out of the question. As a consequence, the electric field and especially the magnetic-field-aligned electric field, which we now know to be of crucial importance, were long disregarded. Even to this day, only very few attempts have been made at directly measuring electric fields in the outer magnetospere.

The magnetosphere was universally assumed to be populated by a hydrogen plasma from the solar wind, whereas we now know that it is sometimes dominated by oxygen plasma originating in the Earth's own atmosphere. As a result of generally accepted theories, one did not even do the appropriate measurements until recently of outflowing ions and of magnetospheric plasma composition. Much of this delay could have been avoided, if results already known from laboratory plasma experiments had been applied to the space plasma. (In fact, on this basis Hannes Alfvén proposed parallel electric fields as an accelerating mechanism for auroral primaries already in 1958, but the idea was almost universally refuted as contrary to classical theory.)

It is a sobering fact that even after hundreds of satellites had circled the Earth, the generally accepted picture of our space environment was still fundamentally wrong in aspects as basic as the existence and role of electric fields and even the origin and chemical composition of the near Earth plasma itself. In the light of this, how can we believe in detailed theoretical models of distant astrophysical objects, until we have learned - and applied to astrophysics - the lessons of how the real plasma behaves in the Earth's own magnetosphere.

2. THE MAGNETOSPHERE - IONOSPHERE SYSTEM

The Earth's ionosphere and magnetopshere constitute a cosmical plasma system that is readily available for extensive and detailed *in situ* observation and even active experimentation. Its usefulness as a source of understanding of cosmical plasmas is enhanced by the fact that it contains a rich variety of plasma populations with densites ranging from more than 10^{12} m^{-3} to less than 10^4 m^{-3} and temperatures from about 10^3 K to more than 10^7 K (equivalent temperature). Even more importantly, this neighbourhood cosmical plasma is the site of numerous and complex plasma physical processes which for example lead to particle acceleration and element separation. The understanding of these processes should be essential also to the understanding of remotely observed astrophysical phenomena that take place in plasmas that will remain out of reach of *in situ* observation (Fälthammar *et al*. 1978; Haerendel 1980, 1981; Fälthammar 1985). For example, one of the outstanding characteristics of cosmical plasmas is their ability to efficiently accelerate charged particles. Many kinds of particle acceleration take place in the near Earth plasmas, and this allows us to study in detail the mechanisms responsible.

A basic reason why the near-Earth plasmas are so active in terms of plasma physical processes is the coupling that the geomagnetic field imposes between the hot thin magnetospheric plasma, which is dynamically coupled to the solar wind and the cool, dense inospheric plasma, which is tied by friction to the Earth (Vasyliunas 1972; Greenwald 1982).

This situation causes an exchange of momentum and energy between the two regions. The exchange is executed through electric currents - the Birkeland currents - flowing between them. Both directly and indirectly (through the instabilities and acceleration that they cause) the Birkeland currents also lead to an exchange of matter between the magnetosphere and the ionosphere. The exchange of matter is selective, so that the chemical composition of the ionospheric plasma that populates the magnetosphere is very different from that of its source. The very efficient element separation that hs unexpectedly been discovered in the near-Earth plasma, and is accessible to <u>in situ</u> investigation there, should also be of considerable astrophysical interest.

The present paper will concentrate on some crucial aspects of the magnetosphere-ionosphere system, namely the electric fields and currents and their role in particle acceleration, plasma transport and chemical separation.

3 BIRKELAND CURRENTS

A phenomenon of paramount importance for the coupling between the magnetosphere and the ionosphere is that of Birkeland currents. In addition to being prime agents for exchange of <u>momentum</u> and <u>energy</u> between the two regions they also play an important role in redistributing <u>matter</u> between them. The energy coupling between the magnetosphere and ionosphere by means of the Birkeland currents was recently discussed by Sugiura (1984).

A reason why the Birkeland currents are particularly interesting is that, in the plasma forced to carry them, they cause a number of plasma physical processes to occur (waves, instabilities, fine structure formation). These in turn lead to consequences such as acceleration of charged particles, both positive and negative, and chemical separtion (such as the preferential ejection of oxygen ions). Both these classes of phenomena should have a general astrophysical interest far beyond that of understanding the space environment of our own Earth.

3.1 The distribution of Birkeland currents

Although predicted by pioneers like Birkeland and Alfvén the existence of electric currents connecting the magnetosphere and ionosphere apparently came as a surprise to many. In fact the first measurements revealing the magnetic effects of what we now call Birkeland currents were initially interpreted as standing Alfvén waves above the auroral zone (see Dessler 1984).

Since then the Birkeland currents have been investigated by means of many satellites. Their general large scale distribution at low altitude (Fig. 1) is well established and described in an extensive literature. Much of the knowledge as of 1983 is summarized in the AGU Geophysical Monograph 28 edited by Potemra (1984). A concise review of field aligned as well as ionospheric current systems was given by Baumjohann (1983). Recent papers on the distribution of Birkeland currents are those of Potemra et al. (1984), Zanetti et al. (1984), Araki et al. (1984), Iijima et al. (1984), Potemra and Zanetti (1985) and Hruska 1986. A new Birkeland current system, flowing in and out of the polar cap and intensifying during periods of northward interplanetary magnetic field has recently been described by Iijima et al. (1984). It is referred to as the NBZ system (for Northward B_z). Birkeland currents in the polar cusp have a pronounced dependence on the y-component of the interplanetary magnetic field. These currents may reflect the most direct coupling between the solar wind generator into the ionsophere (Potemra et al. 1984; Potemra and Zanetti 1985; Clauer et al. 1984; Clauer and Kamide 1985; Zanetti and Potemra 1985).

Very recently the dependence of Birkeland currents and plasma convection patterns on B_y have been investigated by means of Dynamics Explorer data both for southward and northward B_z (Burch _et al_. 1985; Reiff and Burch 1985).

In recent theoretical studies Kan _et al_. (1984) and Marklund _et al_. (1985) have investigated the role of partical blocking of secondary Birkeland currents in causing the rotation of the ionospheric electric field pattern observed during substorms. The degree of closure of secondary Birkeland currents (associated with gradients in the height integrated ionospheric Pedersen conductivity) also plays a key role in a new model of the westward travelling surge developed by Rothwell _et al_. (1984).

Within the large scale Birkeland currents there exist fine structures in the form of thin current sheets with extreme current densities. A case reported by Burke _et al_. (1983) and Burke (1984) is shown in Fig. 2. The sharp downward and upward slopes of the narrow dip in the magnetic field component B_y correpond to a pair of thin upward and downward Birkeland current sheets. The upward current sheet had a latitudinal extent of less than 2 km and an average current density of $135 \cdot 10^{-6}$ A m^{-2}. In the downward current sheet of the same event the current density was $15 \cdot 10^{-6}$ Am^{-2}. The authors note that the upward currents were carried by electrons that appeared to have fallen through a potential drop of a few kV. Also, the observed electron population, the relation between current density and accelerating voltage nearly (but not quite) agreed with adiabatic motion in the mirror field. (The voltage or the source plasma density or both would need to be a little higher than estimated.) The measured electron temperature, about 200 eV, did not indicate any substantial heating, which would be expected if anomalous resistivity played a major role. For the downward currents, which could readily be carried by upflowing cold ionospheric electrons, conditions at the 1000 km satellite altitude are close to the limit for ion cyclotron instability.

Recently Bythrow _et al_. (1984) have reported very high current densities - up to $94 \cdot 10^{-6}$ Am^{-2} - also in earthward currents (measured by HILAT). From the current to the plates of the ion drift meter the authors estimated an ion number density of $2 \cdot 10^{10}$ m^{-3} and hence a magnetic-field aligned drift velocity of 30 km/s for the electrons carrying the Birkeland current. They concluded that this should be enough to destabilize electrostatic ion acoustic waves as well as electrostatic ion cyclotron waves. Simultaneous measurements of electron fluxes indicated that 2 - 4 km equatorward of this Birkeland current the height-integrated Pedersen conductivity had a sharp gradient (2 ohm^{-1} km^{-1}), which in combination with a prevailing nortward electric field could be the cause of the observed Birkeland current.

Small scale current structures have been observed not only near the ionosphere but even in the equatorial region Thus it has been shown by Robert _et al_. (1984) that most of the SIP's (short irregular pulsations) observed at GEOS-2 are in fact the magnetic signatures of localized current structures passing by the spacecraft at a high velocity. The structures are estimated to have a current density of $6 \cdot 10^{-9}$-$3 \cdot 10^{-7}$ Am^{-2}, a size of 20 - 900 km and to move at a velocity of 15 - 170 km/s. They are associated with large electric field spikes (3 - 25 mV/m).

3.2 Driving electromotive forces

One may distinguish between two kinds of electromotive forces that can drive Birkeland current. One is the _MHD_ dynamo action of the bulk motion of plasma in the solar wind, plasma sheath and outer magnetosphere. The other is due to charge separation generated by differential drift of charged particles (gradient and curvature drift). This kind of generators draws on the kinetic or thermal energy of individual particles and may be characterized as _thermoelectric_. Both these kinds of generators are likely to be important in the magnetosphere (see _e_. _g_. Block 1984 and Vasyliunas 1984).

An internal source of MHD dynamo action is the forced rotation of the ionosphere. (To this average contribution is added the dynamo action of ionospheric winds.) The corotational dynamo has an e.m.f. of nearly 100 kV (the equator being negative and both poles positive). However, most of this e.m.f. connects to low- and mid-latitude plasmas. These have a low ohmic resistance and a small enough moment of inertia that they are easily forced to corotate. Thus the net e.m.f. of the circuit, and hence the Birkeland currents, stay nearly zero.

The high latitude part, from the auroral ovals to the poles, still accounts for about 10 kV of the corotational e.m.f. This is small, but not negligible, compared to the externally applied polar cap potential.

Although in the case of the Earth the internal dynamo plays a minor role, the situation can be different in other magnetospheres (for a review see e.g. Hill 1984). Thus Jupiter's magnetospheric processes seem to be dominantly powered by the rotation of the planet. In this case the Jovian satellite Io and its plasma torus are important as an external load (Shawhan 1976, Eviatar and Siscoe 1980). Rotational dynamo action has also been proposed to be important at Uranus (Hill et al. 1983).

Of external sources there are both (1) MHD-type dynamos (the solar wind, the plasma sheet and regions of the magnetosphere where convection field is externally enforced e. g. by a viscous-like interaction) and (2) thermoelectric generators (regions where the gradient and curvature drifts produce charge separation, see e.g. Block 1984, Atkinson 1984a, Vasyliunas 1984).

It is outside the scope of the present paper to discuss the dynamos themselves. These are well described in the literature and for recent reviews the reader is referred to e. g. Stern (1983, 1984). Only one aspect will be briefly discussed, namely the possible role of spatially small-scale dynamo regions and corresponding fine-structure in the ionosphere magnetosphere coupling.

It has been suggested by Heikkila (1982), Lemaire (1977) and Lemaire et al. (1979) that plasma from the magnetosheath is injected in the form of clouds into the magnetosphere. Until they lose their momentum these clouds would form localized and temporary MHD-dynamo regions on closed field lines. In addition they would create regions where, due to curvature and gradient drifts, the plasma would contain both protons of solar wind origin and magnetospheric O^+ ions. It has been suggested by Lundin (1984) and Lundin and Dubinin (1985) that such clouds would form dynamo regions by polarization due to the differential motions of the different types of ions.

A general expression for the differential flow vector of two ion species has been derived by Hultqvist (1984). From measured values of particles and fields he estimated that terms containing pressure gradients and transverse electric currents could easily reach values of some hundreds of km/sec, and that also inertia terms and the magnetic gradient terms could approach 100 km/sec with quite resonable assumptions about characteristic times and characteristic lengths.

Thus determination of electric field from particle fluxes could be uncertain by tens of mV/m even if local particle distribution functions were known exactly (but not their gradients or whether variations were temporal or spatial).

The concept of intruding plasma clouds as localized generator regions for auroral arc structures has been further elaborated by Stasiewics (1984a, 1985). As the localized cloud dynamo drives Birkeland currents to the ionosphere and back magnetic field aligned potential drops may develop in the upward current branch. As a necessary but not sufficient condition for this to happen Stasiewics (1984a) concludes that the scale has to be so small that the characteristic dimension is less than $3(B_i/B_m)r_{ge}$, where B_i/B_m is the ionospheric to equatorial magnetic field strength ratio and r_{ge} is the electron gyro radius in the equatorial plane. These considerations are applied also to nightside plasma ion clouds such as have been known for a long time (de Forest and McIlwain, 1971).

4. REDISTRIBUTION OF PLASMA

We know know that ionospheric ions contribute significantly to populating many regions of the magnetosphere (in addiin to the obvious one, the plasmasphere). They are also present in all energy ranges from thermal to high energy. It started with the discovery by Shelley _et al_. (1972) of precipitating O^+ with energies up to 12 keV and was later followed by the first direct observations of the O^+ ions leaving the ionosphere (Shelley _et al_. 1976). Consequences for magnetosphere ionosphere coupling were discussed by Sharp and Shelley (1981). Reviews of the ionosphere as a source of magnetospheric ions was given by Shelley _et al_. (1982), Horwitz (1982), Sharp _et al_. (1985) and Yau _et al_. (1985). For recent results related to this topic see _e. g_. Lennartsson _et al_. (1985), Stokholm _et al_. (1985), Ipavich (1985), Baker (1985), Waite _et al_. (1985). Only recently has the composition of the bulk of the storm time ring current been measured (Gloeckler _et al_. 1985). Then, too, it is found that injection of ionospheric ions is important.

The presence of ionospheric ions in the magetospheric plasma has of course important consequences both macroscopically (_e g_. by local-dynamo effects, as mentioned above) and microscopically (by their influence on wave propagation, instabilities and wave particle interaction). Heavy ions of ionospheric origin may also influence the localization and initiation of plasma sheet instabilities during substorms (Baker _et al_. 1985b).

A comprehensive collection of papers on the distribution of hot energetic ions in the magnetosphere are found in a recent book edited by Johnson (1983), see also Hultqvist (1983a,b, 1984). Even very energetic (112-157 keV) O^+ ions have recently been observed in the plasma sheet (Ipavich _et al_. 1984). In a review

Hultqvist (1985) emphasizes that present knowledge of low energy plasma in the magnetosphere is very far from complete and improving this knowledge is greatly needed. We may note that in the auroral acceleration region the incomplete knowledge of the low energy plasma introduces a considerable uncertainty in stability analyses, as discussed for example in the recent review by Kaufmann (1984). See also Lennartsson et al. (1985). A schematic overview of sources, transport and acceleration of plasma in the magnetosphere according to Collin et al. (1984) is shown in Fig. 3.

At low and middle latitudes storm-time depletion of the plasmasphere are followed by a diffusive refilling process that takes 7-22 hours (Horwitz et al. 1984).

On polar cap field lines a supersonic streaming of ionospheric plasma - the polar wind - has long been predicted for theoretical reasons. These were initially discussed by Hanson and Pattersson (1963) and Dessler and Michel (1966), later formalized by Axford (1968), Banks and Holzer (1968) and others; for a review see Cowley (1980). The polar wind has been observed by the Dynamics Explorer spacecraft (Gurgioli and Burch 1982, 1985; Nagai et al. 1984; Waite et al. 1985). In addition to the theoretically expected cold polar wind there are also substantial fluxes of suprathermal (above 100 eV) field-aligned O^+ ions that seem to have been subject to some other acceleration processes. Persoon et al. (1983) have compared polar cap electron density profiles determined by the DE-1 plasma wave experiment and earlier, lower altitude observations. They conclude that in addition to a subsonic to supersonic transition at about 1000 km altitude there is a transition from collision dominated to collision free outflow at about 1.5 - 2 R_E. Over the polar cap, DE-1 observations recently reported by Waite et al. (1985) show outward flow of suprathermal low energy (less than 10 eV) O^+ ions with fluxes exceeding $2 \cdot 10^{12}$ m^{-2} s^{-1}, mainly from a region near the dayside polar cap boundary. The integrated source strength is estimated to be $7 \cdot 10^{24}$ s^{-1} for quiet (K_p less than 3) and $2 \cdot 10^{25}$ s^{-1}. The distinction between classical polar wind outflow and O^+ enhanced suprathermal flow has recently been analysed by Moore et al. (1985).

The extraction of ionospheric ions is related to the Birkeland currents both directly through exchange of charge carriers and indirectly by parallel and perpendicular ion acceleration mechanisms driven by the Birkeland currents.

Observations of upflowing ions from the auroral zone and polar cap were recently reviewed by Yau et al. (1984). The total outflow of ionopsheric ions into the magnetosphere, according to Collin et al. (1984) from S3-3 data, are given in Table 1. Locally, upward oxygen ion fluxes exceeding 10^{14} m^{-2} have been observed with DE-2 at 900 km altitude and account for a substantial fraction of the simultaneously observed Birkeland currents (Heelis et al. 1984)

A direct effect of Birkeland currents is due to the fact that the closed-loop current, of which the Birkeland currents are a part, is carried by different particle species in different parts of the loop.

Possible consequences at ionospheric levels were discussed by Block and Fälthammar (1968, 1969) who showed that this effect can modify the F-region density distribution and contribute to the formation of F-region troughs. As the density depletions are associated with loss of ionospheric ions to the magnetosphere, it was also suggested that "the ionosphere and magnetosphere might form a more or less closed loop for the plasma" (Block and Fälthammar 1969). Recent computations by Cladis and Francis (1985) indicate that oxygen ions in the storm-time ring current may go through such a closed loop.

At the magnetospheric end the consequences of the transition of current carriers has been analyzed in a series of papers by Atkinson (see Atkinson 1984a and references therein). If Birkeland currents carried predominantly by electrons connect to transverse magnetospheric currents carried largely by ions, depletions or enhancements should occur depending on the direction of the Birkeland currents. Thus, inward Birkeland currents would cause enhancements of magnetospheric plasma and outward currents would cause depletions. Another example: if part of the cross-tail electric current is deviated through the ionosphere, plasma accumulates in the morning side and evacuates in the evening side of the magnetosphere. According to Atkinson (1984b) the distribution of Birkeland currents at ionospheric altitudes can thus be used to diagnose plasma redistribution in the outer magnetosphere. A steady state model developed on this basis has recently been further extended to include thick adjacent current sheets mapping to the whole plasma sheet (Atkinson 1984c).

A particularly interesting exchange of mass between the ionosphere and the magnetosphere is the outflow of heavy ionospheric ions in the form of "beams" and "conics" (see e.g. Gorney <u>et al</u>. 1981), both because of the acceleration mechanisms of which they bear witness and because they show that very effective chemical separation can take place in a cosmical plasma. The latter could have important consequences in the context of astrophysical abundance considerations.

In the <u>beams</u> the distribution function has its maximum along the magnetic field. However, considering the limits set by instrument resolution some of them may be post-accelerated conics masquerading as beams. They appear to be accelerated by an electric field, and contain information about the potential drop between their source and the observation point. However, they do not give a simple quantitative measure of this potential, because it is obvious that they have also been subject to non-adiabatic processes. For example, their energy spread (50-150 eV) is much greater than would be expected (0.2 eV) if ionospheric O^+ had only fallen adiabatically through a potential drop. It is also well established (Kintner <u>et al</u>. 1979; Cattell 1981; Kaufmann and Kintner 1982, 1984) that there is very close correlation between ion beams and electrostatic hydrogen cyclotron waves. As described in the recent review by

Kaufmann (1984) the typical observed distribution functions of the ion beams may be explained if it is assumed that these waves are the result of the instability of the beams. The typical beam temperatures of 50-150 eV are approximately such that the beams should be marginally stable to generation of hydrogen cyclotron waves. As the ascent through the mirror field tends to narrow the distribution, the beams would, in this scenario, be kept near the limit of instability. This would also mean that at high altitude the beams would have such a width as to efficiently prevent them from reaching the opposite hemispehre. Hence the non-observation of downgoing beams.

The conics have a maximum in their distribution function at a non-zero value of transverse to parallel velocity ratio and are apparently the result of a transverse acceleration followed by expulsion by the magnetic mirror force. Two main explanations of the transverse acceleration have been proposed. One main explanation invokes waves, either electrostatic ion cyclotron waves (Ungstrup et al. 1979; Lysak et al. 1980; Papadopoulos et al. 1980; Ashour-Abdalla et al. 1981; Singh et al. 1981, 1983; Dusenberry and Lyons 1981; Okuda and Ashour-Abdalla 1981, 1983; Ashour-Abdalla and Okuda 1983, 1984; Okuda 1984; Gurnett et al. 1984;) or lower hybrid waves (Chang and Coppi 1981; Retterer et al 1983; Singh and Schunk 1984). In a two-component plasma of stationary hydrogen and oxygen ions and drifting electrons preferential heating of either hydrogen or oxygen can take place depending on the ratio of electron drift speed and the ratio of hydrogen to oxygen concentration (Ashour-Abdalla and Okuda 1983). For a given critical drift the maximum perpendicular heating is generally larger for the oxygen ions than for the hydrogen ions (Ashour- Abdalla and Okuda 1984). Both theoretical analysis and numerical simulation were used and gave results in good agreement. Recently Nishikawa et al. (1985) studied ion heating by hydrogen cyclotron waves, such as are often observed on auroral field lines, using analytical methods as well as numerical simulations. Much stronger heating resulted for oxygen ions than for hydrogen ions. As pointed out by Horwitz (1984) transverse acceleration of O^+ ions is also favoured by the fact that due to greater inertia they have a longer residence time in the acceleration region. Recent results reported by Gorney et al (1985) indicate that the residence time and hence the heating of upflowing ions may be much enhanced by downward pointing parallel electric fields.

Kintner and Gorney (1984) searching the S3-3 data found only one case of perpendicular ion acceleration and broadband plasma waves at the satellite. The wave mode could not be identified, but the electric field of the waves was, in all cases, smaller than required by present theories.

Several authors (Mozer et al. 1980; Lennartsson 1980; Kletzig et al. 1983; Yang and Kan 1983; Greenspan 1984; Borowski 1984) have considered electrostatic shocks or similar electrostatic structures as an alternative or complementary explanation of the transverse acceleration. In this case, too, it is found that the heavier ion species are preferentially accelerated and tend to become less field-aligned. Whereas Yang and Kan (1983) consider this an auxiliary mechanism (to cyclotron heating), Borovsky (1984) finds in his simulations that the particles become more field-aligned as the ion cyclotron waves grow and therefore suggests that the ion conics produce the waves rather than vice versa.

According to Cattell (1984) the S3-3 data indicate that both electrostatic ion cyclotron waves and electric field gradients contribute to the energizing of the ions but that neither is sufficient to account for the observed energy.

A major difficulty in clarifying the processes leading to formation of beams and conics is the limited knowledge of cold background electrons and ions (Kaufman 1984). The present state observational knowledge of low energy plasma outside the plasmapause has recently been reviewed by Hultqvist (1985). Cf. also Stokholm et al. (1985).

5. MAGNETIC-FIELD ALIGNED ELECTRIC FIELDS

One of the crucial questions in magnetosphere-ionosphere coupling is the ability of the plasma to support magnetic-field aligned ("parallel") electric potential drops and thus electrically and dynamically decouple the two regions. This property is also intimately related to the ability to carry Birkeland currents and to energize charged particles.

There has now for some time been an almost complete consensus that such electric fields do exist and that they play an important role in energizing auroral particles. It is, however, also clear that parallel electric fields alone cannot account for all the observed features of the accelerated particle populations. A recent review of parallel electric fields, with extensive references to the literature, has been given by Fälthammar (1983). The present discussion will be limited to general outlines and comments on some recent developments.

5.1 Possible types of parallel fields

A central problem concerning parallel electric fields is what forces are responsible for balancing the dc electric force on the charged particles. On the basis of the kind of force involved, the parallel electric fields can be divided into three categories (Fälthammar 1977, 1978). The three forces are:

1. The net force from wave fields. In the magnetosphere only the electric part of the wave field, and only its component parallel to the magnetic field, can contribute apppreciably to the momentum balance. The prime example of this case is that of anomalous resistivity. The collisionless thermoelectric effect proposed by Hultqvist (1971) would also belong to this category.

2. The magnetic mirror force. Magnetic mirror supported parallel fields have been extensively invoked in explaining observed particle distributions above the auroral zone.

3. Inertia forces. A final possibility is that the force from the electric field is balanced by the inertia of the charged particles themselves. This is the situation in electric double layers. Such are well known from the laboratory and are often considered to be important in space, too.

It is very likely that these categories occur in combinations. E.g. in the presence of a parallel field supported by the magnetic mirror force, strong wave activity may still substantially change particle distributions. Or, numerous weak electric double layers may appear and disappear at random with a result very much resembling a state of anomalous resistivity (Block 1972, 1981).

Each of these categories of electric fields has its own peculiarities. A couple of these will be mentioned here.

Anomalous resistivity requires that the wave electric field along the magnetic field (and a fortiori the total wave field) has an rms value well exceeding (probably by a factor of 10 or more) the d.c. field that it supports: $E_{rms} \gg E_{dc}$ (Shawhan et al. 1978). Although the existing wave fields are not known in enough detail for an accurate evaluation, it can be estimated that anomalous resistivity might account for parallel d.c. fields of the order of mV/m. This could still be enough for supporting several kilovolts, but the potential drop would have to be distributed over distances of the order of one or more Earth radii.

Another feature of the anomalous resistivity is that the power is dissipated locally. For the current densities known to prevail above the aurora, any appreciable parallel field supported by anomalous resistivity would imply extremely rapid heating of the local plasma of the order of eV/sec (Block and

Fälthammar 1976; Block 1984).

In a plasma with two ion species, anomalous resistivity may also lead to selective ion acceleration. A numerical simulation by Mitchell and Palmadesso (1984) showed that the momentum transferred from the waves mainly affected one ion species (H^+) leaving the other (O^+) to be freely accelerated in the d.c. electric field. From numerical simulations Rowland and Palmadesso (1983) concluded that low frequency ion cyclotron turbulence can limit the high velocity runaways via pitch angle scattering. From comparisons between simulations and DE observations electron precipitation bursts Lin and Rowland (1985) suggest that anomalous resistivity does play an important role in connection with particle acceleration.

Parallel electric fields supported by the magnetic mirror force could in principle exist even in the absence of a current, as suggested by Alfvén and Fälthammar (1963) and recently discussed by Serizawa and Sato (1984). Mostly however, the upward mirror force is invoked in the context of upward Birkeland currents, where the principal current carriers are impeded by the magnetic mirror force.

In this case, too, the maximum field strength that can be supported should typically be of the order of a few mV/m. Thus, any large potential drops would have to involve large distances along the magnetic field.

As shown by e. g. Knight (1973), Lemaire and Scherer (1974, 1983) and others the current voltage relation for mirror-supported fields is, under certain assumptions, linear over 2 or 3 powers of ten in voltage and current. For a mirror-supported field this is a relation between the current density and the total voltage drop, not a local relation between current density and electric field at any given part of the flux tube. Thus there does not exist a conductivity, only a conductance. For typical plasma sheet parameters this conductance is $3 \cdot 10^{-6}$ A $(mV/m)^{-1}$ (Fälthammar 1978). This holds, however, only <u>provided</u> the loss cone of the source plasma is continually replenished. Otherwise the conductance can be reduced to arbitrarily low values. Furthermore, it has been shown by Yamamoto and Kan (1985) that the current density can be substantially reduced relative to that given by the Knight-Lemaire formula, if the potential drop is concentrated at altitudes as low as 4000 km.

Correspondingly, there should be a relation between energy flux and accelerating voltage such that in a certain energy range the former is proportional to the square of the accelerating voltage. Such a relation has been confirmed by Lyons <u>et al</u>. (1979) and Menietti and Burch (1981). A linear rather than quadratic relation was reported by Wilhelm (1980) but this seems to be explainable in terms of a spatial variation of the source plasma.

<u>Electric double layers</u> represent the opposite extreme in terms of spatial distribution. The thickness L of a double layer with voltage drop V in a plasma of electron temperature T_e is of the order of

$$L = C\ (eV/kT_e)^{1/2}\ {}_D \qquad (2)$$

where ${}_D$ is the Debye length and the factor C is of the range 10-100 (Shawhan <u>et al</u>. 1978).

An important feature of the double layer is that the power released goes into energetic particles that deposit their energy remotely and therefore there is no problem of excessive local heating.

5.2 Observational evidence

The earliest observations interpreted as evidence of parallel electric fields were those of field alignment and narrow energy peaks in precipitating electron fluxes. Gradually the evidence accumulated and now includes both observation of

(1) natural particle populations, (2) motion of artificially particles injected by measured active experiments and (3) direct measurements of electric fields. At the same time it has become abundantly clear that the situation is not simple, and that d.c. electric fields alone cannot explain all the characteristics of observed particle spectra. In the following will be given a very brief summary of observations interpreted as evidence for parallel electric fields as well as objections against this interpretation. For a more complete review and references to the original papers, see e.g Fälthammar (1983) and, for particle observations, Kaufmann (1984).

I. Observations of natural particle populations

In addition to the field alignment and narrow energy peaks already mentioned, there is a large amount of satellite data showing characteristic structures in the particle distribution functions. These include occurrence of an <u>acceleration boundary</u> in downcoming electron distributions, similar to what would be expected if the particles had been accelerated in a potential drop of a few kV. Another important feature is a <u>widened loss cone</u>, as would be expected from a potential drop below the satellite (again in the kV range). <u>Upstreaming ion beams</u>, if assumed to have passed an electrostatic accelerated ion region, indicate a potential drop below the satellite that is in rough agreement with the widened electron loss cone.

While most observations of accelerated particle populations have been made at altitudes of a few hundred to a few thousand kilometers, an inverted V event observed at 13 R_E has recently been reported (Huang <u>et al</u>. 1984) showing that at least sometimes the acceleration region can be very far away.

Low voltage (tens of V) upward pointing electric fields - perhaps analogous to the wall sheath in a laboratory plasma - have been reported by Winningham and Gurgiolo (1982). Equatorward of the morning side polar cusp the electrons that carry the downward Region 1 Birkeland currents appear to be accelerated by potential drops of tens of V at altitudes of several thousands kilometers (Burch et al. 1983).

Although the magnitude of the potentials of parallel electric fields can be estimated from existing particle data, the determination of their spatial distribution is much more difficult. As shown by Greenspan et al. (1981) even distinguishing between double layers and smoothly distributed electric fields is difficult with existing data and would require accurate high resolution measurements of low energy electrons (around 100 eV and less). As the distribution functions often vary appreciably within a satellite spin period multiple detectors with high time resolution would be needed. To extract the information carried by the upstreaming ions a wider energy coverage would also be desirable (see e. g. Kaufmann 1984).

A number of objections were already long ago raised against the interpretation of auroral particle distributions in terms of parallel electric fields (O'Brien 1970; Whalen and McDiarmaid 1972; Whalen and Daly 1979). For example, Hall and Bryant (1974) considered that the shape of the angular distribution of electrons and of the width of the energy peak were indicative of a stochastic acceleration process. Wave particle interaction was also invoked by many authors to explain the width of the energy peak and the occurence of multiple peaks (for references see Hall et al. 1985). The velocity space features (acceleration boundary, widened loss cone) are diffuse and the velocity space region that corresponds to trapping between the electric field above and the magnetic mirror below is populated. The upcoming ion beams are much wider than could be explained by electrostatic acceleration alone. These and other difficulties with purely electrostatic acceleration were summarized by Bryant (1983). Although some of these objections can be eliminated even within adiabatic models (cf. e. g. Block 1984; Brüning and Goertz 1985; Lotko 1985) it is of course not surprising that non-adiabatic processes play a role, too (cf. par. 5.3 below).

II. Active experiments

The first active experiments to indicate the existence of parallel electric field were shaped charge Ba releases (Haerendel et al. 1976), where a clear acceleration of the Ba ions could be seen (in one case corresponding to a voltage drop of 7.4 kV at an altitude of 7500 km). This seems to be one of the most conclusive observations, of the existence of a parallel electric field. By now a total of half a dozen such experiments have been made. The main results of these have been compiled in a recent paper by Stenbaek-Nielsen et al. (1984).

Active experiments have also been made using electron beams ejected from a rocket to probe the parallel electric fields. Reflexions of the electrons were observed, which are compatible with the existence of parallel electric fields above the rocket but do not constitute a proof (Wilhelm et al. 1984, 1985). If interpreted in terms of parallel electric fields they indicate field strengths of 1 - 2 mV/m above about 2500 km and potentials of at least a few kV or more.

III. Electric field measurements

Direct electric field measurements at high and low altitudes have shown different latitude distributions that imply the existence of parallel electric fields at intermediate altidues (Mozer and Torbert 1980). The discovery by direct measurements of the so-called electrostatic shocks, i.e. regions of strong (hundreds of nV/m) over short distances (a few km) imply that electric field mapping along electrically equipotential magnetic field lines does not apply. In a static situation this would irrevocably imply the existence of parallel electric fields somewhere between the ionosphere and the satellite. However, it cannot be excluded that this lack of mapping may instead be due to the induction field of an oblique Alfvén wave as proposed by Haerendel (1983), cf. par. 5.3.

Although it was in the past often considered that strong electric double layers ($V>>kT_e/e$) would exist over the auroral zone, direct electric field measurements indicate that they are limited and rare, if they exist at all (Boehm and Mozer 1981). On the other hand occurrence of numerous weak double layers have been discovered (Temerin et al. 1982; Hudson et al. 1983) and seem to be able to account for integrated potential drops of the order of several kV.

5.3 Some recent developments

Parallel electric fields have usually been considered to be important mainly in regions of upward current flow becuase outflowing ionospheric electrons were thought to provide copious current carrying capability for downward currents. However, theoretical works by Newman (1985) has shown that also downward parallel electric fields may exist. The key to this is the existence, at the low altitude end of the field line, of an ambipolar diffusion region with an upward directed electric field of a few eV. This is found to be sufficient to exponentially reduce the densities of electrons and ions enough that a net downward electric field above would not extract excessive electron current. Very recently observations have been reported by Gorney et al. (1986), where the phase space distributions indicate acceleration by a downward pointing electric field with a potential of a few tens to a few hundreds of volts over the altitude range of 1000 - 6000 km.

In a recent Ba jet experiment Stenbaek-Nielsen et al. (1984) noticed a sudden decrease in the speed of progression of the tip of the jet as it reached 8100 km altitude. Their interpretation was that at this altitude the barium was accelerated rapidly upward to a sufficient speed that the density decreased below detectability. For this to happen through energization by wave fields and subsequent magnetic-mirror expulsion, the authors estimate that gyroresonant waves in excess of 25 mV/m would have been required. They therefore favour a d.c. electric field as the only plausible explanation. From a detailed study of the brightness distribution they estimate a lower limit to the strength of the d.c. field. The result is that the potential must have been in excess of 1 kV. Because of the limited resolution of the TV images only an upper limit (200 km) could be set to the distance over which the potential drop occurred. Hence the field strength must have been at least 5 mV/m.

One important observation in this case was that as the Ba jet itself drifted (westward), and auroral arc segments drifted through it (from south to north), no apparent corresponding changes were seen in the behaviour of the barium. The situation persisted for at least 10 minutes. Thus the observed electric field appears to have been a large-scale horizontal structure and not associated with individual arc structures. Of course this does not exclude arc-related parallel electric fields still higher up. The simultaneously observed background luminosity at 6300 - 4278 Å corresponded to a characteristic energy of the precipitating electrons of about one keV.

Not unexpectedly, parallel electric fields alone are insufficient to account for all features of auroral particle distributions. Features that seem to require other explanations have been pointed out by several authors. These features were summarized by Bryant (1983), who favours an entirely different approach aimed at explaining the auroral acceleration entirely by wave-particle interactions without recourse to a d c electric field. Recently this approach has been expounded in a series of papers (Bingham et al. 1984, Hall et al. 1984, 1985 and references therein). The acceleration mechanism favoured by these authors is lower hybrid waves driven by ion beams streaming torward the Earth in the plasmasheet boundary. Referring to the ion beams reported e. g. by DeCoster and Frank (1979) and the wave observations of Gurnett and Frank (1977) and Mozer et al. (1979) the authors find that (1) the energy of the beams is easily sufficient to power the auroral acceleration and (2) the normalized energy density of lower hybrid waves on auroral field lines is high.

However, the electric field of these waves is very nearly transverse to the magnetic field and it is only the parallel component of the wave electric field that can contribute to the field-aligned acceleration. Therefore more detailed knowledge of the wave fields seems to be necessary to assess with certainty what effect the waves have on the particles. Furthermore, as some of the evidence of for field aligned parallel fields - such as the acceleration of artificial ions beams - remains intact, attempts to explain auroral acceleration entirely without paralle d c fields appears problematic, and a combined approach more promising.

The combined effect of (ion acoustic) wave turbulence and a dc parallel electric field has ben analyzed by Stasiewics (1984b,c), using the quasilinear Vlasov equation to estimate the runaway region in velocity space. One of the results is a new interpretation of the classical type of peaked auroral spectrum (see Fig. 4). The accelerating potential, U, is not given by the energy at the peak, but by the difference between this energy and the energy at the minimum of the spectrum. The latter energy is in typical cases about 1 keV and is related to the energy required for electron runaway in the presence of the wave field. A theoretical prediction of its value is, however, not possible without much better knowledge of the actual wave spectra in the interaction region than is now available.

For the low energy electrons, region I in Fig. 4, the spectral form E^{-1} is ascribed to the heating of the trapped electrons and not to atmospheric backscatter (Evans 1974). In this interpretation region II in Fig. 4 corresponds to runaway electrons that have fallen freely through the d c electric field of the acceleration region. Hot magnetospheric electrons with velocities exceeding the runaway velocity will pass the acceleration region unimpeded and form region III of the spectrum.

Stasiewicz (1984c) also derived a relation between the voltage and current density that is a generalization of that of Knight (1973) and a corresponding relation between energy at the spectral peak and the precipitating energy flux. When the energy at the peak is much larger than the source plasma temperature, this relation reduces to the quadratic form that applies in the adiabatic case (Lundin and Sandahl 1978).

As already mentioned the occurrence of numerous weak double layers and solitons have been known from electric field measurement at high altitude on the satellite S3-3. According to recent results reported by Boehm et al. (1984) and Kellog et al. (1984) similar structures exist even at rocket altitudes (above 200 km). In both cases the observations were made by means of double probe electric field experiments. But in neither case was the experiment designed for this unexpected discovery. Therefore the information on the size and motion of the structures is still incomplete.

In the flight reported by Kellog et al. (1984) a lower limit to the typical voltage drop of the double layer like structures was determined to be 0.4 V. In the corresponding structures observed by Boehm et al. (1984) the electric fields, mostly parallel to the magnetic field, were typically 50 mV/m and the corresponding potentials at least 0.1 V. However the lower limit of the potentials observed varied up to 2 V. No limit could be set on the size of the structures but a lower limit of their velocity was estimated to be 15 km/s. In addition closely spaced soliton-like structures were observed with electric fields greater than 1 mV/m.

Further measurements with dedicated instrumentation is necessary to clarify the nature of these phenomena.

6. CONCLUDING REMARKS

For a proper understanding of astrophysical phenomena, theoretical analysis, which by necessity must rely on simplifying assumptions, must be guided by empirical knowledge of how real plasmas behave. Laboratory experiments have an essential role to play in this context, but _in situ_ observations of the magnetospheric plasma can, in some respects, provide us with an even better knowledge of plasma behaviour in natural conditions. The plasma in the magnetosphere (including the ionosphere) and the solar wind are the only cosmic plasma accessible to extensive _in situ_ observations and experiments.

Observations of magnetospheric plasmas extend our empirical knowledge to a new range of plasma parameters by many powers of ten. It is also fortunate that plasmas in the Earth's neighbourhood cover such wide ranges of density and temperature and that magnetosphere-ionosphere interactions cause a rich variety of plasma processes to take place.

The truly fundamental progress in the understanding of the magnetospehre has only begun. Important observational discoveries have opened a new epoch in magnetospheric research. The knowledge already obtained, and the insights still to be gained, in magnetospheric research should be of great value in understanding astrophysical plasmas and may have important inpacts on astrophysics.

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CAPTIONS

Fig.1 Schematic Birkeland current patterns according to Reiff and Burch (1985) for various orientations of the interplanetary magnetic field. The upper row is for strongly northward B_z and B_y going from postitive (A) through zero (B) to negative (C). The lower rows are for B_z weakly northward (middle row) and southward (bottom row). Patterns to the left are for positive B_y and to the right for negative B_y.

Fig.2 Magnetic field signature of a pair of thin, high-density current sheets within the evening Region 1, Birkeland current (Burke 1984). The steep gradients on either side of the narrow dip beginning at 11.48.16 UT correspond to outward and inward Birkeland current sheets of $135 \cdot 10^{-6}$ A m^{-2} and $15 \cdot 10^{-6}$ A m^{-2} respectively.

Fig.3 Schematic overview of sources, transport and acceleration of plasma in the magnetosphere according to Collin *et al.* (1984).

Fig.4 New interpretation of inverted-V electron spectra according to Stasiewics (1984c). The acceleration voltage v is now related to the difference of the energies E_p at the peak and E_r at the minimum.

TABLE 1. The Estimated Terrestrial Ion Outflow in the Energy Range 0.5 to 16 keV for O^+ and H^+ During Magnetic Storms and Quiet Times

	Range	Mean
Quiet Time		
H+	$0.7–1.4 \times 10^{25}\ s^{-1}$	$1.1 \times 10^{25}\ s^{-1}$
O+	$0.15–0.4 \times 10^{25}\ s^{-1}$	$0.27 \times 10^{25}\ s^{-1}$
Total	$0.85–1.8 \times 10^{25}\ s^{-1}$	$1.3 \times 10^{25}\ s^{-1}$
O+/H+	0.1–0.4	0.25
Storms Time		
H+	$1.5–4.5 \times 10^{25}\ s^{-1}$	$3.0 \times 10^{25}\ s^{-1}$
O+	$3.5–5.0 \times 10^{25}\ s^{-1}$	$4.2 \times 10^{25}\ s^{-1}$
Total	$5.0–9.5 \times 10^{25}\ s^{-1}$	$7.2 \times 10^{25}\ s^{-1}$
O+/H+	0.7–2.1	1.4

The range indicates the uncertainty of the estimate resulting from both counting statistics and uncertainties in the identification of the newly outflowing ions.

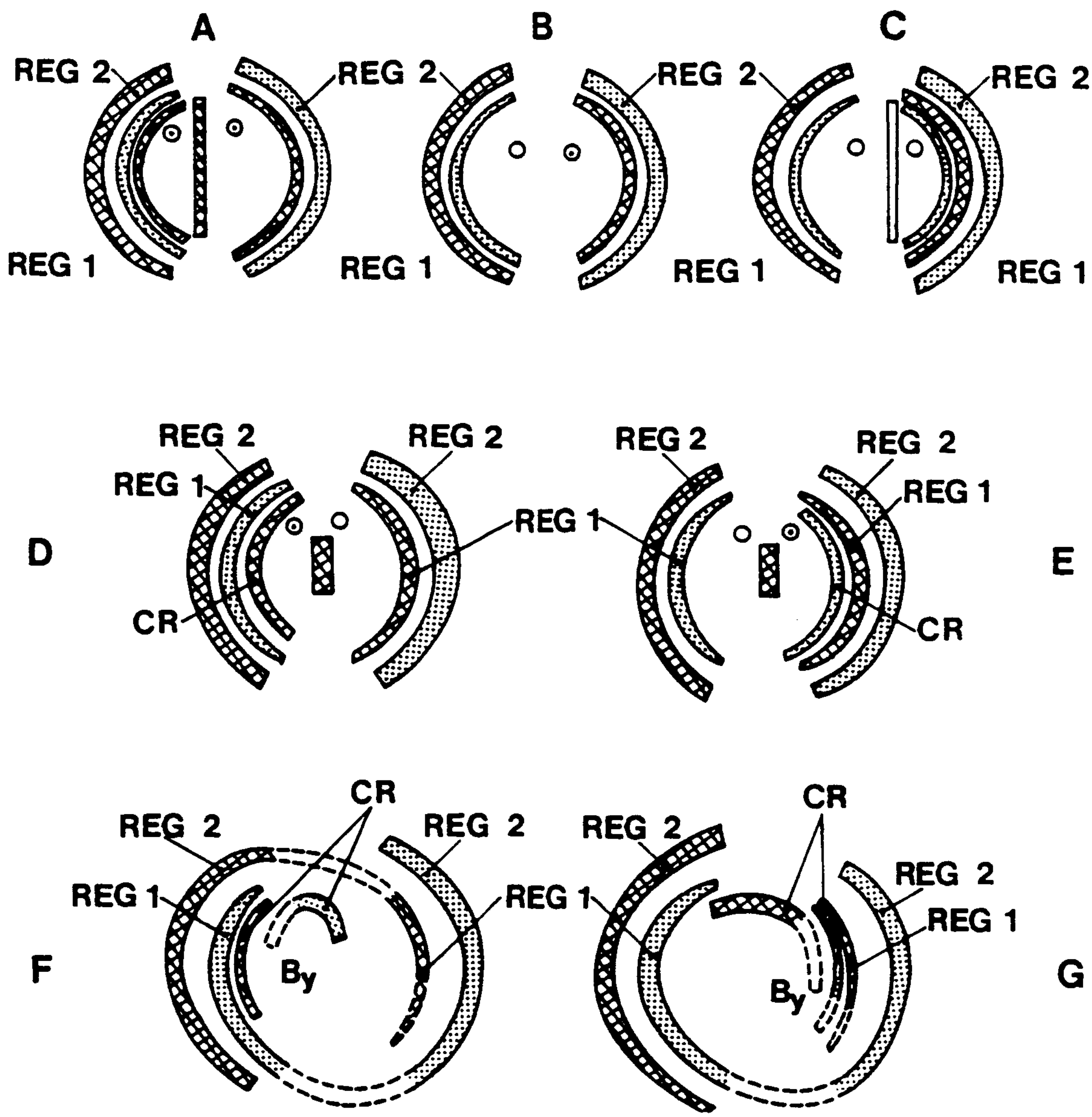
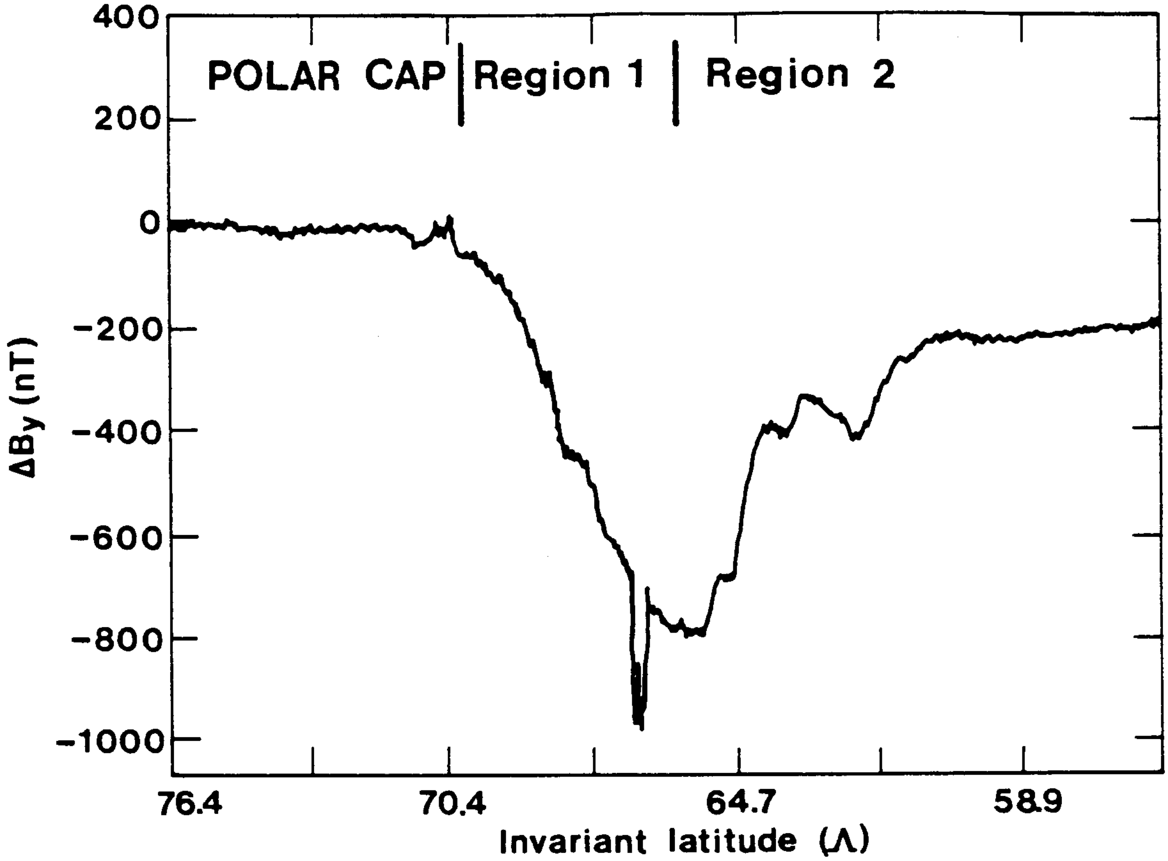
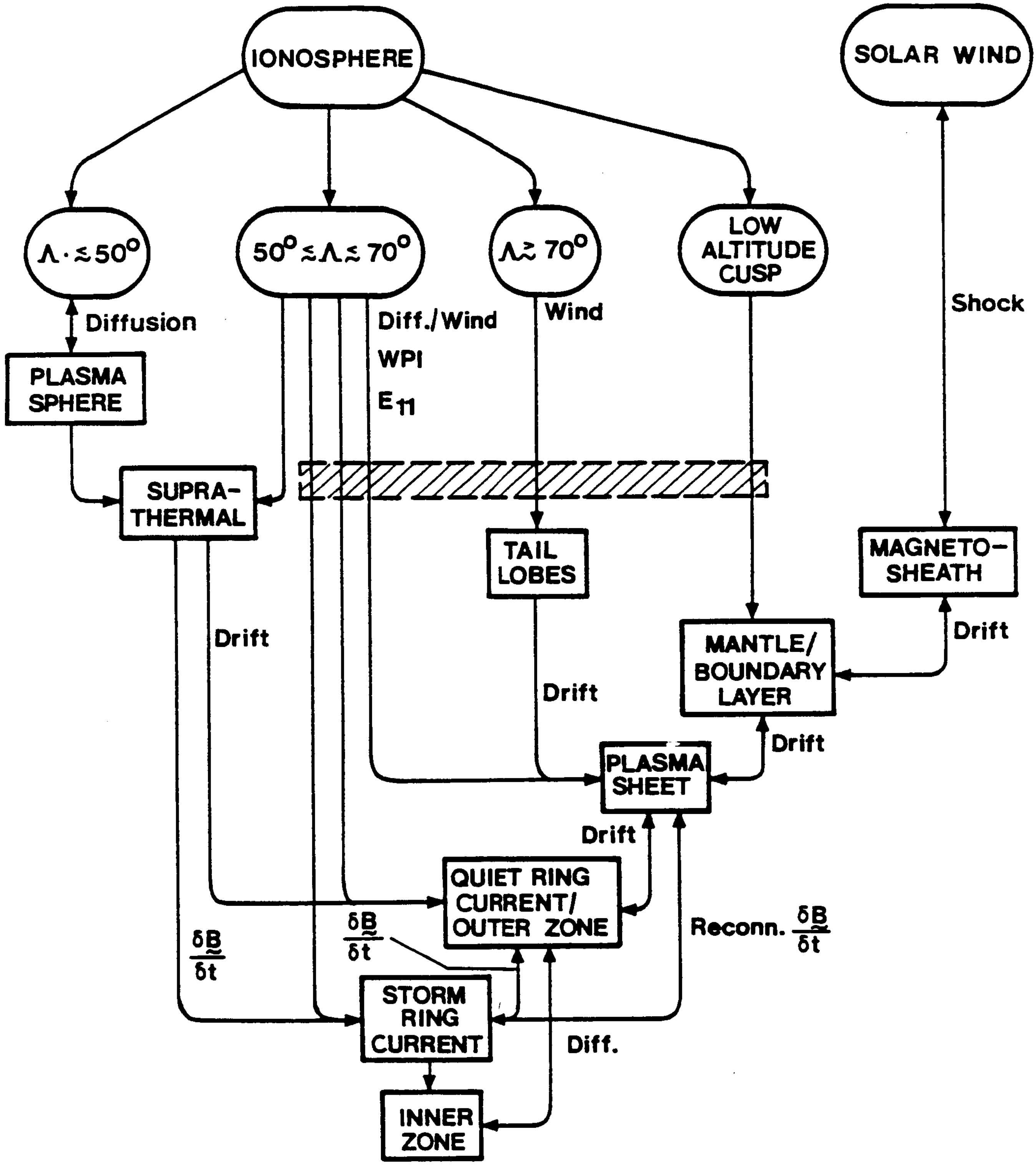


Fig. 1



POLAR CAP
Region 1
Region 2
400
200
0
-200
-400
-600
-800
-1000
ΔBy (nT)
76.4
70.4
64.7
58.9
Invariant latitude (Λ)

Fig. 2



IONOSPHERE
SOLAR WIND
Λ ≲ 50°
50° ≲ Λ ≲ 70°
Λ ≳ 70°
LOW ALTITUDE CUSP
Diffusion
Diff./Wind
WPI
E11
Wind
Shock
PLASMA SPHERE
SUPRA-THERMAL
TAIL LOBES
MAGNETO-SHEATH
Drift
MANTLE/ BOUNDARY LAYER
Drift
Drift
Drift
PLASMA SHEET
Drift
QUIET RING CURRENT/ OUTER ZONE
δB/δt
δB/δt
Reconn. δB/δt
STORM RING CURRENT
Diff.
INNER ZONE

Fig. 3

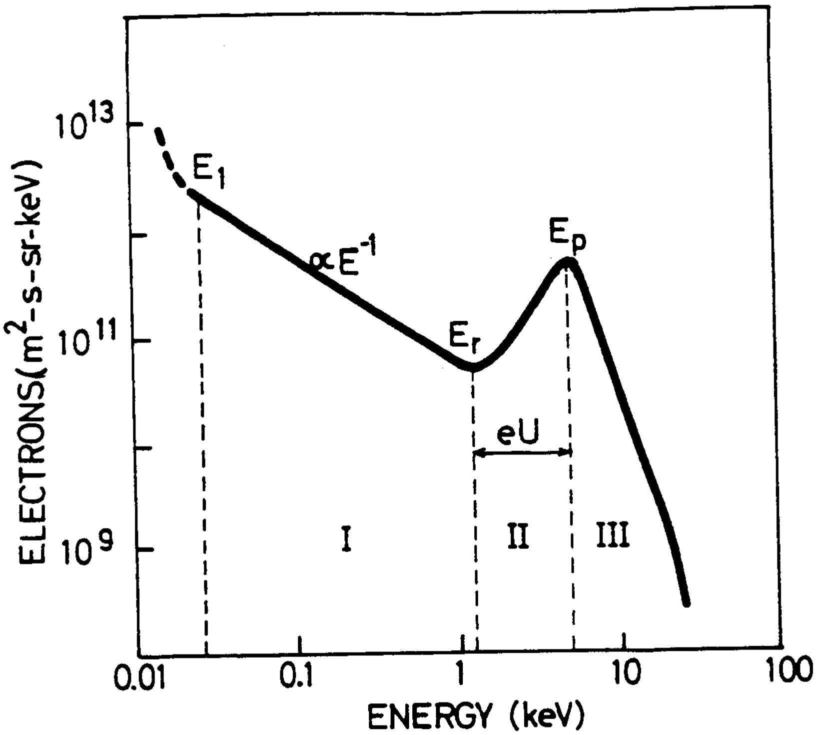

10^13
10^11
10^9
ELECTRONS (m^2-s-sr-keV)
E1
∝E^-1
Ep
Er
eU
I
II
III
0.01
0.1
1
10
100
ENERGY (keV)

Fig. 4