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THE EARTH'S MAGNETOSPHERE AS A SAMPLE OF THE PLASMA UNIVERSE

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ABSTRACT

Plasma processes in the Earth's neighbourhood determine the environmental conditions under which space-based equipment for science or technology must operate. These processes are peculiar to a state of matter that is rare on Earth but dominates the universe as a whole. The physical, and especially the electrodynamic, properties of this state of matter is still far from well understood. By fortunate circumstances, the magnetosphere-ionosphere system of the Earth provides a rich sample of widely different plasma populations, and, even more importantly, it is the site of a remarkable variety of plasma processes. In different combinations such processes must be important throughout the universe, which is overwhelmingly dominated by matter in the plasma state. Therefore, observations and experiments in the near-Earth plasma serve a multitude of purposes. They will not only (1) clarify the dynamics of our space environment but also (2) widen our understanding of matter, (3) form a basis for interpretating remote observations of astrophysical objects, thereby even (4) help to reconstruct events that led to the evolution of our solar system. Last but not least they will (5) provide know-how required for adapting space-based technology to the plasma environment. Such observations and experiments will require a close mutual interplay between science and technology.

1. INTRODUCTION

Before scientific instruments had access to space the physical picture of space used to be a very simple one. It was based on the limited information carried by the small part of the electromagnetic spectrum that can reach the Earth's surface through the obscuring blanket of the atmosphere.

This changed greatly after access to Earth orbit allowed the previously inaccessible infrared, ultraviolet, X-ray and gamma-ray wavelength bands to be used for remote sensing of distant cosmic objects.

In the new wavelengths, cosmic objects often appear very different. By an analogy introduced by Hannes Alfvén, what was revealed is as different from our visual picture of the universe as an X-ray picture of a man's body is different from a visual light photo of it - and correspondingly more revealing: while "the visual picture is literally superficial ... the X-ray picture ... shows the skeleton and intestines and gives a better understanding of how his body works".

What the new picture of our universe reveals is, among other things, that not only in terms of the dominating state of matter, but also in terms of physical processes, our universe is a <u>plasma universe</u> (Alfvén, 1986a). This being the case, the results of <u>in situ</u> observations in near-Earth space plasma take on a new significance as an indispensible complement to remote observations.

Since at this workshop we are going to look decades ahead, let us start by briefly recalling how the past couple of decades changed our concept of space surrounding the Earth. The pre-space-age concept of space was essentially one of a structureless void. Once scientific instruments could make direct measurements in space, the surprises started coming. The Störmer forbidden regions, rather than being empty, were copiously populated so as to form radiation belts. The geomagnetic field, rather than asymptotically approaching a dipole, terminated abruptly at the sunward limit of what we now call the magnetosphere. This so-called Cahill discontinuity, later identified as the sunward magnetopause, was the first and unexpected example of a sharp boundary separating the previously unstructured continuum of space into physically different regions. The early exploration of the magnetosphere was curtailed not only by understandable prejudice - e. g. nobody's instrument looked downward from satellite orbit to detect upstreaming ions coming from the ionosphere - but also by the state of the art in detector technology. This favoured measuring fluxes of relatively energetic particles over e. g. measuring medium and low energy plasmas. Gradually, the complexity of the magnetosphere grew, until in the late seventies all the major large-scale plasma regions were known.

However, even after this "modern" picture of the space environment, with most of the now known plasma regions, had been established, the origin of the magnetospheric plasma was still largely misconceived. Thus, until only a few years ago it was presumed as a matter of course that the plasma populating the magnetosphere was a (somewhat contaminated) hydrogen plasma from the sun. We now know that a major - and at times dominating - constituent is oxygen originating in the Earth's own atmosphere. (At the most recent solar terrestrial physics symposium a few months ago it was questioned whether there is any major contribution to magnetospheric plasma other than the terrestrial one (Chappell, 1986).)

The fact that such a misconception of the Earth's own close environment could prevail even after hundreds of satellites had circled the Earth, should inspire caution in considering the composition and properties of other invisible cosmic objects, whether they be stellar interiors, interstellar plasma, pulsar magnetospheres or intergalactic cosmic rays.

Similarly, any of the new insights into the physics of matter in the plasma state, which have been or will be gained in the Earth's magnetosphere, must be essential also for interpreting in correct physical terms the remote sensing results of astrophysical objects, visible and invisible, that can never be studied in situ. For example, one of the outstanding characteristics of cosmical plasmas is their ability to efficiently energize charged particles. Many kinds of particle energization do take place in the near Earth plasmas, where the mechanisms responsible can be studied in detail, and theories can be confronted with decisive tests. This has already given much insight into these mechanisms, but much still remains to be clarified. Based on the resulting understanding of how space plasmas really behave, one may with some confidence interpret also remotely observed manifestations of plasma processes in astrophysical plasmas. In fact, lessons learned in the Earth's magnetosphere must give important clues not only to the astrophysics of our contemporary universe, but also to events in the past, such as the evolution of our own solar system, which undoubtedly took place in a plasma environment.

It has also become clear that the near Earth space environment is one that puts severe requirements on scientific and technical equipment in Earth orbit. To meet these requirements it is, again, important to understand the complex plasma processes which control this environment but which are, themselves, still far from well understood.

The reasons why the ionosphere-magnetosphere system is so useful as a potential source of knowledge is briefly discussed in Section 2. Taking full advantage of this system as a potential source of knowledge requires an improved understanding of the system itself beyond what has so far been achieved. This, in turn, requires observations that have not yet been performed to a sufficient accuracy or a sufficient extent - or at all. In particular a better knowledge is needed of the electric currents and electric fields in the magnetosphere (Sections 3-4). The achievement of such observations also requires technological developments. Closely related to the electric fields and currents are the mechanisms of release of magnetic energy and of chemical separation (Sections 5-6). Some processes essential to the plasma universe, which do not take place spontaneously in the near-Earth plasma, can be reproduced there by active experiments. An example of this is discussed in Section 7. It is concluded (Section 8) that *in situ* observations and experimentation in the Earth's own magnetosphere should be an essential complement to remote sensing of distant objects.

2. THE MAGNETOSPHERE - IONOSPHERE SYSTEM

The usefulness of the Earth's magnetosphere-ionosphere system as a source of understanding of cosmical plasmas is enhanced by the fact that it contains a rich variety of plasma populations with densities ranging from more than 10^{12} m^{-3} to less than 10^4 m^{-3} and (equivalent) temperatures from about 10^3 K to more than 10^7 K. However, even more importantly, this neighbourhood cosmical plasma is also the site of numerous and complex plasma physical processes.

The 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 ionospheric plasma, which is tied by friction to the Earth.

Primarily, this coupling causes an exchange of *momentum* and of *energy* between the two regions. This exchange is executed through electric currents that flow between them - the Birkeland currents. Both directly and indirectly (through the instabilities and energization 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 magnetospheric plasma that has come from the ionosphere has a chemical composition which is very different from that at its region of origin. This very efficient chemical separation, which has unexpectedly been discovered in the near Earth plasma, and is accessible to *in situ* investigation there, should also be of considerable astrophysical interest. It shows that plasma physical processes, unrecognized until recently, can cause great changes in abundance ratios even over distances that are, on a cosmical scale very small.

3. ELECTRIC CURRENTS

3.1 Current conduction in space plasma

Perhaps the most basic property of matter in the plasma state is its ability to carry electric current. The importance of this ability - and of its limitations - in the plasma universe follows from the fact that practically all cosmical plasmas are magnetized, and that the magnetic field is intimately coupled to the dynamics of the plasma. Except close to celestial bodies, where internally generated magnetic fields can be large, the sources of the magnetic fields in a cosmical plasma are currents that flow in the plasma itself. Even in the Earth's magnetosphere, major, and in the outer parts dominating, contributions come from currents in the plasma.

In classical plasma theory, the ability of a plasma to carry current was assumed to be well understood and its resistivity described in terms of a simple formula. According to this formula most cosmical plasmas would have negligible resistivity. Consequently ideal magnetohydrodynamics and the so-called frozen field condition were believed to be valid, and were applied both to the Earth's magnetosphere and to astrophysical plasmas. In the case of the magnetosphere, we now know, from *in situ* observations of the real space plasma that its electrical properties are much more complicated. The concept of the magnetospheric plasma as a simple magnetohydrodynamic medium has been shattered, and even the concepts of a locally defined resistivity or conductivity can cease to be meaningful. Rather than being a virtually resistanceless conductor of electric current along magnetic field lines, the real magnetospheric plasma can have a very limited capability of carrying electric current and can be capable of supporting magnetic-field-aligned electric fields with voltage drops of many kilovolts. (This particular aspect will be further discussed in Section 4.) Indeed, some of the most interesting physics of the magnetosphere, such as the auroral process, seems to critically depend on this non-classical behaviour of the space plasma.

Also closely related to the plasma's limited ability to carry electric current is the excitation of various current-driven instabilities. It has been suggested by Alfvén (1981) that plasmas fall into two distinct categories: "active" and "passive" plasmas, and that in general a plasma becomes "active" when it is forced to carry an electric current.

Another important aspect is how the electric currents are driven. In an ideal MHD medium the only emf available would be the $\underline{v}\times\underline{B}$ electric field, which can tap energy from the mass motion of the plasma. In the real space plasma another important possibility is that the plasma can act as a "thermoelectric" generator, tapping energy from the random motion of energy-rich particle populations.

In the magnetosphere both these sources of electric current seem to be important, but still very little is known about how the magnetospheric currents are driven.

In fact, the magnetosphere offers an excellent study object. The ultimate source of energy for most of the magnetospheric current systems is the solar wind, but the way its energy is fed to the interior of the magnetosphere is very complex and probably involves establishing internal secondary generators of both MHD and thermoelectric type. The study of this process should contribute much to the understanding of the electrodynamics of other cosmical plasmas, wherever energy is exchanged between interacting plasma regions.

Still another aspect of the way space plasmas carry electric current is filamentation. Filamentary structure is a pronounced feature of many astrophysical plasmas. From laboratory plasma experiments we know that plasma currents have a tendency toward filamentation. In the case of cosmical plasma the connection between filamentation and electric currents is not very well known, and studies of this in the magnetosphere should help clarify this problem.

A related problem is that of current sheets and their possible relation to a "cellular" structure of space (Alfvén, 1981). In the magnetosphere there are two major current sheets (at the magnetopause and in the tail), one of which is related to a boundary separating plasma region with different physical properties.

3.2 Measurement of electric currents in space

Although the magnetic fields in the magnetosphere have been measured routinely since the beginning of the space age, the knowledge of the geometry of magnetic field lines, and hence the magnetic conjugacy of widely separated plasma regions is still rather limited (cf *e.g.* Lui and Krimigis, 1984). Even more limited is the knowledge of how the sources of the magnetic field, *i. e.* the *electric currents*, are distributed in the magnetosphere. Since, in a mathematical sense, the electric current can be calculated if the magnetic field is known, it was long considered that the electric current itself was an uninteresting quantity. However, since in the real magnetosphere the plasma has a rather limited ability to carry electric current, and since many important processes like the auroral acceleration seem to depend critically on the current density, the electric current is indeed a relevant quantity.

Furthermore, what happens at a given point in a current-carrying plasma depends not only on the local conditions but on the whole circuit of which it is a part, *i. e.* we are faced with fundamentally *non-local* problems. For this and other reasons it is important to know how electric currents in space close, and how they are carried (*e.g.* what kind of charge carriers and what terms in the generalized Ohm's law are important). Knowledge of how the current systems close is also important in the context of large-scale auroral electrodynamics. For example, uncertainty of how the Birkeland currents close in the outer magnetosphere is an obstacle to the understanding of the substorm process. The importance of knowing the electric currents in order to understand cosmical plasmas has been eloquently spelled out by Alfvén (1981, 1986b).

Unfortunately, determination of the electric current systems in the magnetosphere is difficult. Very important progress has been made in determining the structure of the Birkeland currents, especially near the ionosphere, using satellite-borne magnetometers. However, from single point measurements of the magnetic field the electric currents can only be determined if suitable geometric assumptions can be made, e.g. that the current flows in sheets. Such assumptions may be appropriate for Birkeland currents at intermediate altitudes in the ionosphere, but they become increasingly questionable with increasing distance. In order to make a unique determination of the local electric current density with existing techniques one would have to make very accurate measurements of the magnetic field at four points separated by distances small relative to the scale of current density variation. Although in principle possible with a multiple spacecraft mission, this has not yet been achieved or even attempted.

We know that very fine scales appear in auroral forms and in auroral electric fields. We do not know to what extent they are associated with current density variations on corresponding scales. These fine structures would hardly be accessible to multipoint measurements, and with present technology they would even be hard to detect at all by means of magnetometers, because the resultant magnetic field change over an individual structure is minute.

Especially for measurement of the fine structure of electric current but also for mapping out the large-scale current systems it would be extremely desirable to develop techniques for directly measuring the local current vectors. No such technique exists at the moment, but it is very interesting that attempts are now being made to develop one, using the Faraday effect in optical fibres. This principle of current measurement is already being used in high power technology. However, to be used in space its sensitivity has to be increased by many powers of ten. This poses a great technological challenge. If successful, this new technique could be one of the most important contributions to space plasma physics in the decades to come. (It should be noted that direct current measurements do not replace magnetic measurements but are a greatly needed complement.)

4. ELECTRIC FIELDS

Unlike most other physical quantities in the magnetosphere, the electric field was not subject to direct measurement until late in the space age. The reason for this was in part that the measurements are technically difficult and in part that, according to over-idealized theoretical models of the magnetospheric plasma, the electric field was believed to be of little significance. We now know that these theoretical models are of limited values in the real space plasmas, and that direct measurements of electric fields are important. However, until now, very few satellites have been equipped to measure them, except in low orbit, and extensive measurements throughout (relevant parts of) the magnetosphere is still a task that largely remains to be performed.

4.1 General properties

The direct measurements that have been made so far have confirmed some of the expected properties, such as the existence, in an average sense, of a general dawn-to-dusk electric field. However, they have also shown that the electric field in the outer magnetosphere has large time and space variations, which often exceed the average value. Indeed it is likely that these variations in the electric field are a more important aspect of it than the average. Also, it has become apparent that induction fields play an important role. For this reason the usefulness of quantitative models representing the average configuration of the electric field is much more limited than in the case of the magnetic field.

4.2 Fine structure of auroral electric fields

One of the surprising discoveries of the S3-3 satellite was the occurrence over the auroral oval of extremely strong localized electric fields (Mozer et al., 1977). These phenomena, which came to be called "electrostatic shocks", are apparently associated with the auroral acceleration process. However, whether they are indeed essentially electrostatic or are of a different nature, e.g. associated with Alfvén waves as proposed by Haerendel (1983), is not yet known, and a different nomenclature may be appropriate. More detailed data now being taken by the Viking satellite (Viking Science Team, 1986) may perhaps help solve this problem. The Viking data show good agreement in terms of the intensity of the fields (several hundred mV/m) with earlier measurements, but are also able to resolve more of the fine structure. The fine structure of the electric fields above the aurora is probably an important feature of the auroral acceleration process and deserves much more attention in terms of direct measurements than it has had until now. It should be one of the important tasks of future space plasma research.

4.3 Magnetic-field-aligned electric fields

Perhaps the most important question concerning electric fields in the magnetosphere is whether any substantial electric field components do or do not exist along the geomagnetic field (Alfvén and Fälthammar, 1963). It is closely related to the question of the current-carrying ability of a collisionless plasma. When the existence of such fields was suggested long ago (Alfvén, 1958), it was almost universally rejected as impossible, because it was incompatible with prevailing theoretical ideas. Since then evidence of many kinds has accumulated.

The observational indications of parallel electric fields are now numerous and include:

. Precipitating auroral electrons with an "acceleration boundary" in velocity space.

. Upgoing beams of ions with a distribution function indicative of passage through a potential drop.

. Artificial ion beams injected upward from the ionosphere and observed to undergo sudden accelerations along the magnetic field.

. Artificial electron beams injected upwards and reflected in a way consistent with a potential barrier above (although other interpretations may not be excluded).

. Comparisons of electric fields measured at high and low altitude, which show that the spatial distributions differ in a way consistent with a parallel electric field prevailing in the intervening altitude range.

. Electric field measurements revealing the existence of numerous small-scale "electric double layers", which together may account for substantial potential drops.

. Measurement of large parallel components associated with strong localized auroral fields.

Due to this rather massive evidence the existence of parallel electric fields, at least above the aurora, is now widely, although not universally, accepted. It should, however, also be pointed out that parallel electric fields cannot alone account for all the features of auroral acceleration processes. Various kinds of wave particle interactions must contribute, too. (For a recent review of the evidence and references to the extensive original literature, see e.g. Fälthammar, 1986).

However, in spite of all these indications, very little is known about the actual properties of the parallel electric fields. For example, only the general altitude range where they belong is known, but not their detailed structure or other properties. Nor is it known what mechanism allows these electric fields to exist. There is only a small number of possibilities (Fälthammar, 1978). They are:

. The magnetic mirror force

. Electric fields of waves, with an intensity much larger than the parallel dc field

. Electric double layers

Their relative roles are unknown. At least the magnetic mirror force seems to be essential, but probably all of them play some role.

The existence and nature of parallel electric fields is a very fundamental question in the electrodynamics of matter in the plasma state. It also has important implications for the behaviour of cosmical plasmas. For example, one of the characteristics of cosmical plasmas is their ability to energize charged particles. Parallel electric fields allow such energization to take place much more efficiently than by stochastic processes. Furthermore, since parallel electric fields (with a non-vanishing curl) are a necessary condition for violating the "frozen field condition", the existence of such fields has direct implications for the coupling between magnetic fields and velocity fields in cosmical plasmas. E. g. unfreezing of magnetic fields seems to explain certain observations in comet tails (Ip and Mendis, 1976). If it occurs in the surroundings of rotating cosmical bodies, it may invalidate the law of isorotation. In a cosmogonic context it may be important in order to allow partial corotation (Alfvén and Arrhenius, 1976).

Because of these important aspects of parallel electric fields it should be a high priority task to study them experimentally in the regions of the Earth's magnetosphere where they exist.

4.4 Technical aspects

Part of the reason why direct electric field measurements by in situ probes were started late was the technical difficulties involved. Especially in the thin and hot plasmas of the outer magnetosphere, the requirements are stringent. Direct probe measurements require not only large probe separation and high configurational symmetry, but in adddition the spacecraft body and all its protrusions must have a high degree of electrostatic cleanliness, i.e. very nearly constitute a single equipotential surface.

Special precautions have to be taken to suppress possible errors from photoelectron clouds or from exchange of photoelectrons between probes and satellite body. Such precautions may involve active control of spacecraft potential, biased guards on the probe-supporting booms, and bias currents to the probes (to achieve an optimum operation point on the voltage-current characteristic of the probes). The probe surfaces themselves are subject to stringent requirements in terms of homogeneity of the work function and should at the same time have as high a photoelectron yield as possible.

It is interesting to note that the same method that is used to ensure the electrostatic cleanliness needed for scientific measurements of the electric field (and, in fact, very low energy particles as well) is well suited to cure the problems of differential charging of applications satellites.

In addition to the probe techniques there are others, such as those using artificial ion clouds or beams of electrons or ions, which have until now been used even less. Each method has its advantages and limitations, and needs to be technically perfected and used in complementary ways.

Particle measurements have until now provided some of the most convincing evidence of the existence of parallel electric fields. However, as shown by Greenspan et al. (1981), present day instruments do not allow determination of the spatial distribution of the potential drop. Improving the measurement technique to allow measurement down to low energy and a much improved time resolution is desirable. This is another technological challenge, which involves not only increasing the instrument sensitivity but also meticulous precautions to eliminate potentially harmful effects of the plasma environment, e. g. by ensuring strict electrostatic cleanliness of the spacecraft and control of spacecraft potential. These efforts to understand and protect against the plasma environment will of course benefit not only these sensitive scientific experiments but also environment-sensitive space-based technological equipment.

5. RAPID RELEASE OF MAGNETIC ENERGY

Also related to how electric currents are carried is one of the characteristic features of cosmical plasmas, namely the ability to very rapidly release large amounts of magnetically stored energy, e.g. in solar flares. Such rapid release takes place in the magnetosphere, too, namely in the magnetic substorm process. It is generally believed that there are close similarities between solar flares and substorms in terms of how the energy is released, but theories differ about what is the mechanism responsible. If this can be clarified by observations in the magnetosphere, it would probably also help understanding solar flares and other cosmical manifestations of rapid release of energy.

6. CHEMICAL SEPARATION

The discovery of large abundances of oxygen plasma in the magnetosphere is important not only for the understanding of magnetospheric and auroral physics. Its wider significance is to reveal the previously unknown and unexpected facts that
(1) very efficient chemical separation can take place in a cosmical plasma even over cosmically small distances, and
(2) at least one of these mechanisms (there may well be more than one) is available for *in situ* inspection at a convenient nearby location.

Although we know that the mechanism is intimately related with selective energization of plasma ions, there is not yet general agreement on exactly which of the proposed mechanisms is responsible. This is yet another example of a magnetospheric problem, whose solution should have a distinct astrophysical significance. It opens the possibility that astrophysical plasmas located close to each other may still have very different relative abundances of chemical elements.

7. CRITICAL VELOCITY INTERACTION

In addition to plasma phenomena occurring naturally in the magnetosphere, active experiments in the space plasma may further serve to clarify plasma physical processes that are of importance elsewhere. As an example with unusually wide applications ranging from technology to cosmogony we may consider Alfvén's Critical Velocity phenomenon.

The phenomenon was originally postulated by Alfvén as an element of his theory of planet and satellite formation. Years later it was observed experimentally by Block and Fahleson. Subsequently it has appeared in many different experimental configurations including a certain class of experiments for fusion research. Recent rocket experiments have proved that it can operate in space plasma (for a review see Newell, 1985) - which brings the experimental evidence much closer to the parameter range of the original application of the phenomenon.

The Critical Velocity has been invoked in explanations of the interaction of the solar wind with gas clouds from the moon, cometary comae and interstellar gas. Recent observations of the comets Giacobini-Zinner and Halley have been interpreted in terms of the Critical Velocity effect (Haerendel, 1986, Galeev *et al*., 1986). If, as has been proposed (see *e.g*. Papadopoulos, 1983), this effect is responsible for environment anomalies at the space shuttle (optical and IR emissions, enhanced wave activity and energization of electrons and ions), it may also have important technological implications for the design and use of the space station.

8. CONCLUDING REMARKS

Both in terms of the dominating state of matter and in terms of physical processes, the plasma state plays a key role in the Universe, present and past. Thus both in astrophysics and cosmogony, plasma physical processes must be taken into account. The understanding of such processes is still limited, but can be improved by *in situ* observations and experiments in the magnetosphere of the Earth. Such observations and experiments should therefore be an essential complement to the collecting of astrophysical data by remote sensing and should be a challenging task for space science and technology in the decades ahead.

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