TRITA-EPP-78-07

ON THE SIGNIFICANCE OF MAGNETOSPHERIC
RESEARCH FOR PROGRESS IN ASTROPHYSICS

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April 1978

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1. Introduction

Astronomy, and especially astrophysics, is at present in a very interesting phase of development, where remarkable observational discoveries are being made. However, since astrophysical phenomena take place in remote regions, where in situ observations are not possible, and involve matter in various extreme states, it can be very difficult to interpret the observations and to understand the physical phenomena behind them. Usually the states involved are states of magnetized plasma at extremes of temperatures and/or density. Then the interpretation of the observations depends heavily on whatever knowledge of plasma processes is available, either theoretical or experimental.

The difficulties associated with this can easily be understood by recalling the difficulties faced by thermonuclear fusion research two decades ago. The task was to correctly predict the behaviour of a very hot, magnetically confined, plasma. A well developed theoretical formalism existed. It was a generalization of the classical theory of gases to include charged particles, but had so far never been subjected to a thorough experimental verification. Surprisingly it was found that the hot plasmas in thermonuclear machines often behaved quite differently from what had been predicted from existing plasma theories. This necessitated a fresh start, and, as progress was made into new temperature regions, experiments formed the backbone of the theoretical structures. This has led to a much improved foundation for modern thermonuclear work, but even now the complicated behaviour of hot, magnetically confined plasma is far from completely understood.

In astrophysics the situation is so much more difficult because, in contrast to the plasmas in thermonuclear machines, in situ "diagnosis" of the astrophysical objects is not possible.

Until the advent of the space age no cosmic plasma at all had been studied in situ, but now such study is possible, but only in our near space environment.

To understand the significance of this, it is important to realize that our immediate environment in space, the magnetosphere (including the ionosphere) of the Earth and the adjacent interplanetary space, offer a rich sample of plasma states in natural conditions. They include cool, weakly ionized, collision-dominated gravity confined plasmas as well as hot, essentially fully-ionized and virtually collision-less magnetically confined plasmas. While the parameters may still be many powers of ten short of the extreme values attained in some remote astrophysical plasmas, the plasma populations in the magnetosphere represent a large step from the parameter range available in Earth-based laboratories. Study of the magnetospheric plasmas can therefore greatly widen the empirical basis of cosmical physics.

Already, spacecraft observations in the magnetosphere have identified a variety of plasma processes which were not predicted from the classical kinetic formalism, the MHD formalism or even modern plasma theories. In particular, as we shall describe in more detail later, limitations have been found to the validity of the classical concept of the frozen-in-magnetic field, which had been standing in our way as a 'golden rule' in cosmic electrodynamics. For this reason, some recent discoveries are quite fundamental for future progress in cosmic plasma physics. There is little doubt that they will have profound implications in astrophysics.

The need for an improved empirical basis in cosmical physics is dramatically illustrated by the history of magnetospheric research itself. Before in situ measurements were possible, and even for many years after satellite measurements had begun, the magnetosphere was described in terms of highly idealized models that were a heritage from classical plasma physics. They involved infinite conductivity along magnetic field lines, frozen-in magnetic fields and simple magnetohydrodynamics convection. It was tacitly assumed that the matter in the outer magnetosphere was (mainly) hydrogen atoms from the solar wind, and that electric fields - if

they were considered at all - were everywhere transverse to the magnetic field.

For a long time even spacecraft observations failed to reveal the fallacy of such assumptions. This was probably because uncritical use of these assumptions guided the planning and design of the observations. Thus, for example, particle detectors in low Earth orbit always looked only upwards because accelerated particles coming from below - as recently observed - were inconceivable in the prevailing theories.

It is only in the present decade, actually only during the last few years, that magnetospheric physicists generally have found that the classical concepts break down in certain, in fact the most interesting, regions of the magnetosphere.

It is also during the last few years that the significance of Birkeland currents (magnetic-field-aligned electric currents in the magnetosphere) and magnetic-field-aligned electric fields have truly been realized. This new insight has far-reaching consequences in understanding the aurora and other fascinating phenomena in the magnetosphere.

Although the understanding of the magnetosphere has changed gradually over later years a veritable breakthrough has come as a consequence of a few particle and field measurements on one single satellite, S3-3. We now know that

- 1) the frozen field condition cannot be trusted and different levels of the magnetosphere can be electrically decoupled - at least partially,
- 2) magnetic field aligned electric fields with potentials of several kV exist not only in narrow regions but over hundreds of km in latitude,
- 3) ionospheric ions are accelerated along geomagnetic field into the magnetosphere and
- 4) a large, sometimes dominating part of the storm time ring current consists of oxygen from the ionosphere rather than hydrogen from the solar wind.

These and other findings in magnetospheric physics indicate that the really important phase of magnetospheric research, in terms of fundamental physical understanding of plasma behaviour in natural conditions, has only just begun.

This has also far-reaching consequences for the foundations of cosmic plasma physics and hence for astrophysics. If a cosmic plasma system so close to us as the magnetosphere could for such a long time be misinterpreted in terms of the physical processes going on, how sure can we be about the interpretations of astrophysical phenomena known to us only by remote observations? It is of interest to recall that Lord Kelvin estimated the age of the Earth, on the basis of its cooling rate, to be fifty million years, since radioactivity was not known during his generation. It is perhaps not an exaggeration to say that inadequate plasma physical models could lead to - and already have led to - similarly misleading conclusions in astrophysics.

It is also worth emphasizing the importance of laboratory experiments in cosmic plasma physics. In thermonuclear research a great deal of progress has been possible, after the initial setback, because a large experimental effort has guided the theoretical development. Similarly, in cosmic plasma physics, laboratory experiments as well as magnetospheric research are needed to guide the theoretical interpretation of remote observations. One example is the electric double layer phenomenon, which according to recent observational research is likely to occur in the magnetosphere and may have profound consequences in cosmic plasmas. Although its existence has long been known in unmagnetized plasma, and recently proved in magnetized plasma, an adequate theory - especially of its dynamics - does not yet exist, and in all applications one must rely heavily on results of laboratory experiments.

2. The role of magnetization

Virtually any known astrophysical plasma is magnetized. To be precise, a magnetized plasma is defined as a plasma that contains a magnetic field which is strong enough to make the gyroradii of all its charged particles much smaller than the linear dimensions of interest. As the latter are usually large in cosmic plasmas, even a small magnetic field is easily sufficient to make the plasma magnetized.

For example, for stellar dimensions and temperatures of the order of 10^6 K, as in the corona, magnetic fields above 10^{-12} T are sufficient. For galactic dimensions, and even if we consider the highest observed energies, the corresponding number is 10^{-17} T. The smallest cosmic magnetic fields which can be measured or inferred are of the order of 10^{-9} T.

For magnetized plasmas it is often useful to distinguish between three classes, namely high, medium and low density plasmas (Alfvén and Fälthammar, 1963). They are defined in terms of the relative magnitudes of the gyroradius, ρ , the mean free path, λ , and the characteristic linear scale, l_c , as follows:

High density: $\lambda \ll \rho$

Medium density: $\rho \ll \lambda \ll l_c$

Low density: $l_c \ll \lambda$

High density plasmas occur in stellar bodies, lower stellar atmospheres and lower planetary ionospheres. Except for wave propagation they have a high degree of isotropy. Current densities and electric fields obey a simple local relation, Ohm's law.

Medium density plasmas prevail in fairly thin transition regions above the lower stellar atmospheres and planetary ionospheres, but can also occur in regions such as the Earth's plasmasphere. These plasmas are anisotropic in terms of diffusion and electric current conduction. The electric field/current-density relation is still local and can be expressed in the form of a generalized Ohm's law.

Low density plasmas prevail throughout most of the Earth's (and other) magnetosphere(s), the solar corona, interplanetary, insterstellar and intergalactic space. They are the most complicated plasmas, because collective interactions tend to be important instead of the relatively simple binary collisions that prevail in low and medium density plasmas. Numerous kinds of plasma instabilities and wave-particle interactions are possible. In terms of electric properties, a major complication is the fact that there need no longer exist any local relation between electric field and current density. The reason for this is that charge carriers may gain momentum from the electric field in one region and lose it e.g. by magnetic mirroring, in a different region. Low density plasmas in this sense are a major pre-occupation of modern plasma physics, especially in thermonuclear research where $\lambda \gg l_c$ is one of the requirements for magnetic confinement.

In the magnetosphere the most exciting discoveries in recent years are related to the properties of low density plasmas. The consequences for the understanding of cosmic physics in general can be expected to be great.

3. Electric currents and fields in cosmic plasmas

3.1 The concept of conductivity

The magnetization of all cosmic plasmas is connected with electric currents through Maxwell's first equation $\text{curl } \underline{B} = \underline{i}$, and as cosmic magnetic fields are not generally curl-free a fundamental problem is how electric currents are carried by cosmic plasmas (Alfvén 1977).

For high and medium density plasmas this is a fairly simple problem, because the current is determined essentially by a local balance between electric, magnetic and frictional forces. The current-carrying ability of the medium at each point is characterized by a conductivity which in high density plasmas is a scalar, in medium density plasmas a tensor.

In low density plasmas the conduction of current is a very complicated problem. This fact is often overlooked, and classical

conductivity formulas are erroneously applied to low density cosmic plasmas. One illusion is that, as collisions become rare and vanish, the conductivity along magnetic field lines increases and becomes essentially infinite. In reality, the very concept of conductivity loses its meaning in such a case, and an entirely new situation arises, Alfvén and Fälthammar (1963). Presented simple theoretical examples illustrate that there need not exist any local relation such as Ohm's law.

As a result of magnetospheric spacecraft observations in the last few years the fallacy of the conductivity concept in low density plasma has been brought to the surface. This will doubtless be of great consequence in many astrophysical applications, too. In particular, it has become clear that the ability of a low density plasma to carry electric current is far from being "infinite", and that substantial electric fields can be required to drive the Birkeland currents (magnetic-field-aligned) currents of the magnitude (of the order of 10^{-6} Am^{-2}) observed in the magnetosphere. This is of great consequence in astrophysics, because (1) it changes the whole electrodynamics of cosmic plasma, (2) the finite electric field along magnetic field lines violates the concept of frozen-in magnetic field lines and (3) it provides an efficient means of particle acceleration.

The detailed electrical properties of low energy plasmas are still far from well understood, and much further experimental work - in the laboratory and in the magnetosphere - is needed to clarify them. We shall now briefly discuss a few typical phenomena that involve substantial magnetic-field-aligned electric fields.

3.2 Anomalous resistivity

Anomalous resistivity has been recognized for over a decade as a possible means of supporting magnetic-field-aligned electric fields in space plasma. An extensive literature exists on the subject. For a recent review see Papadopoulos (1977). Anomalous resistivity is characterized by wave-turbulence sufficiently strong to impede the current-carrying electrons so that a local Ohm's law is reestablished. The wave turbulence is usually considered to be driven by the current itself, but may, according

to Papadopoulos and Coffey (1974a,b) and Papadopoulos (1975) also be maintained by a separate agent such as a high-energy electron beam that is unstable in the local plasma environment. Whichever the cause may be, the d.c. electric field strength, E , that can be supported is limited by the condition $E \ll E_{rms}$, where E_{rms} is the r.m.s. value of the electric field of the wave turbulence (Fälthammar, 1977). This has also been confirmed by direct measurements in the magnetosphere (Mozer et al., 1977). This restriction can be very important in the case of the magnetosphere (Shawhan et al., 1978).

The wave turbulence will act differently on particles in different parts of velocity space. In particular, particles of sufficient initial velocity (in the direction of the electric force) will become runaways. They will become decoupled from the main population of charge carriers, and the current they carry will not be determined by local conditions but depend on the whole electric circuit involved. Therefore, if the runaway current becomes substantial compared to the total electric current, the local relation between electric field and current is lost. Thus the current is not determined by local "resistivity", and the whole circuit must be taken into account. In this case the term "resistivity" loses its meaning.

The existence of the anomalous resistivity phenomenon has been clearly established in the laboratory (for a review, see e.g. Schrijver, 1973) and wave fields measured in the magnetosphere (for a review, see Shawhan, 1977, and Southwood, 1978) are large enough to support magnetic-field-aligned electric fields of the order of mV/m, which may well integrate to voltage drops of the order of several keV. Such a field is large enough to be of great significance to magnetospheric plasma dynamics. On the other hand, it now appears that, in the magnetosphere, anomalous resistivity may not be the only and perhaps not even the most important, mechanism for supporting magnetic-field-aligned electric fields. Alternative mechanisms are the double layer and the magnetic mirror effect.

3.3 Electric double layers

The electric double layer was discovered by Langmuir as early as 1929; wide interest in the phenomenon has been revived by recent experimental studies by Torvén and Babić (1975, 1976) and Quon and Wong (1976). For a review on double layers with special reference to possible space applications, see Block (1976, 1977).

Like anomalous resistivity, a double layer is typically established as a consequence of current-driven plasma instabilities. To predict theoretically whether the end result of a given instability will be anomalous resistivity or a double layer is extremely difficult. Theoretical studies have therefore often started from the assumption that the end state is one of anomalous resistivity.

The recent laboratory experiments, which show that the result of the instability may well be a double layer instead of anomalous resistivity, illustrate the danger of a purely theoretical approach in this case and the need for empirical experiments on the behaviour of the real plasma.

The electric potential drop across a double layer depends on factors such as density and temperature of the adjoining plasmas and on the electric properties of the circuit in which the current is closed. Thus, unlike anomalous resistivity, the electric double layer does not imply a local relation between electric field and current.

An important difference between double layers and anomalous resistivity is the way in which the dissipated energy is deposited. In the case of anomalous resistivity it is deposited in the ambient plasma at the location of the voltage drop, leading to intense local heating there. In the case of a double layer on the other hand, all particles passing through the layer are "runaways", and form beams that carry away the dissipated energy to be deposited in some other region where the beam is finally stopped. In the magnetosphere this may account for the energy deposition in the polar ionosphere by auroral primaries without excessive heating in the acceleration region. In many astrophysical applications this remote deposition of energy

may be very important.

Direct observations of double layers are difficult because of their small thickness, 10-100 Debyelengths. It can in fact be estimated that the probability of encountering a double layer is one in several hundred satellite passes.

In the recent electric field data of the S3-3 satellite (Mozer et al., 1977) there is one case (of about 200) where the magnetic-field-aligned electric field was reported to be several hundred mV/m. This is entirely compatible with an electric double layer (Shawhan et al., 1977).

3.4 Magnetic-mirror effect

In a low density plasma slight differential anisotropies between positive and negative particles can lead to large magnetic field aligned electric fields even without a net current (Alfvén and Fälthammar, 1963). In the magnetosphere where large field-aligned currents (Birkeland currents) are known to flow to and from the auroral oval, and in many astrophysical situations, the magnetic mirror effect puts an upper limit to the conductance per unit area - a conductivity need still not exist - which above the auroral region of the Earth is at most of the order of a few $\text{Am}^{-2}\text{keV}^{-1}$ (Fälthammar, 1977, 1978). This requires that the loss cone of the source plasma is continually replenished. If not, the current will be choked and the conductance reduced to still smaller values and can in principle approach zero.

4. The frozen field condition

If the classical conductivity formula were applicable to cosmic plasmas, the condition for "frozen-in magnetic fields" would almost be fulfilled. But the plasma properties described in Section 3 may well decouple the electric fields in different portions of a magnetic flux tube (magnetic field unfreezing). This occurs at least in a limited but important region of the magnetosphere above the auroral ovals. Very recently, observations of comet tails (Ip and Mendis, 1976) appear to be the first proof of magnetic-field unfreezing in plasmas outside the Earth's magnetosphere.

Magnetic field unfreezing may also invalidate the law of isoro-

tation, and in the context of planet and satellite formation allow an important phenomenon called partial corotation (Alfvén and Arrhenius, 1976).

5. Particle acceleration

A characteristic property of cosmic plasmas appears to be their remarkable capability of generating suprathermal and high energy particles. How this is achieved is one of the most fascinating problems in plasma physics. In ordinary particle accelerators, insulators and sometimes also tuned harmonic signals are requisites for accelerating charged particles to high energy. None of these requisites are available in cosmic plasmas. Yet we observe cosmic ray particles with energies of 10^{19} eV or more, solar protons of 10^{10} eV and magnetospheric protons of 1 to 10^6 eV. It would be impossible to generate such high-energy particles if the plasma had the simple magnetohydrodynamic properties usually ascribed to it until now.

Some of the particle energization processes in cosmic plasma can be studied in the magnetosphere. Their products range from slightly suprathermal electron fluxes in the ionosphere to ions of several MeV in the radiation belts and in the tail region of the magnetosphere. Some of these acceleration processes involve wave fields due to various instabilities. Others depend on slowly fluctuating transverse electric fields to cause drift-resonant adiabatic acceleration, which can be compounded with non-adiabatic effects. A particularly interesting process is the direct acceleration of charged particles in the magnetic-field-aligned electric fields that can, and do, prevail in low density plasmas. This possibility was earlier excluded by the illusion that magnetic-field-aligned electric fields cannot exist and that the frozen-field condition is valid. In the magnetosphere, such a direct acceleration process seems to play an important role in auroral phenomena (cf Kan and Akasofu, 1976; Block, 1976, 1977; Fälthammar, 1977; Lennartsson, 1977). In the solar atmospheres the field-aligned acceleration may also play an important role in flare phenomena (Carlqvist, 1968), which is widely recognized to have many similarities with magnetospheric substorms (Akasofu and Chapman, 1972).

Field-aligned acceleration may also be important in many other cosmic plasmas. One example on a large linear scale is double radio sources, recently discussed by Alfvén (1978). The energy, originating in the unipolar dynamo of the central galaxy, is carried by electric current to the two opposite remote regions where the current gets unstable and a parallel electric field is established (presumably in a double layer).

Although particles energized in magnetic-field-aligned electric fields will initially not have a large magnetic moment, they are likely to achieve one gradually by nonadiabatic processes. When they have, they will emit synchrotron radiation, which will modify their spectrum by energy degradation.

6. The structure of matter in space

One of the most important results of space exploration is the discovery of a number of boundary surfaces. Some of these layers are due to electric sheet currents which may reverse the magnetic field. This often occurs in the magnetopause, in the neutral sheets of the magnetotail, in the solar equatorial plane (earlier interpreted as "the sector structure"), and in cometary tails. Such boundary sheets may be very thin, sometimes only a few Larmour radii. Their persistence demonstrates that they have a high degree of stability and that cosmic plasmas have a general tendency to divide itself into compartments by setting up such layers.

The discovery of the many boundaries separating different plasmas is remarkable in that neither theoretical considerations nor laboratory experience had led us to expect them. This has profound importance for our picture of the structure of space. We find that space occupied by plasmas tends to be divided in "compartments", often separated by thin current sheets. On the interstellar and intergalactic scale, space may very well have a cellular structure consisting of a large number of separate regions, containing plasmas of different magnetization, density, temperature, and perhaps also different kinds of matter (koino-

and antimatter).

7. Scale considerations

A difficulty in using laboratory experiments to simulate cosmic phenomena is that the scales are different by many powers of ten. Plasma phenomena scale according to certain laws (see e.g. Alfvén and Fälthammar, 1963). For example, the magnetic field strength scales as the inverse of the linear dimension and would in most cases require unattainable values in the laboratory.

One may distinguish between configuration scaling, which endeavours to simulate, on the laboratory scale, the essential features, structural as well as dynamical, of a given cosmic configuration, and process scaling which only requires the local conditions to be sufficiently similar for the same plasma physical processes to occur. An example of the former are terrella experiments reproducing some features of the magnetosphere. An example of the latter is to reproduce current-impeding mechanisms such as anomalous resistivity, double layers or magnetic-mirror support of electric fields. As process simulations involve fewer parameters to simulate and smaller scaling ratios, adequate scaling is much more feasible. Further, an experiment for process scaling can be much more widely applicable, precisely because it is not limited to a specific type of configuration.

Similar considerations can be applied when magnetospheric results are used to clarify astrophysical phenomena. Here the scale ratios can be even larger; one can again distinguish between similarities in terms of configurations and similarities of processes involved. Here, too, similarities of plasma physical processes are the most important ones.

8. Conclusions

For a proper understanding of astrophysical phenomena, it is necessary to let the theoretical work be guided by empirical knowledge of how plasmas behave in nature. 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 plasmas 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. The value of this is easy to see, considering the importance of linear scales in the similarity laws for plasmas. It is also fortunate that the Earth's magnetosphere contains such a rich variety of plasmas, from the relatively dense and cool ionospheric plasma to the extremely thin and hot plasmas at larger distance.

It is only recently that the potentiality of magnetospheric research toward application in astrophysical problems has become apparent. This is largely because truly fundamental progress in the understanding of the magnetosphere has only just begun. It has begun as a consequence of recent observational discoveries that mark a new phase of magnetospheric research. The knowledge already obtained, and the insights still to be gained, in this new phase of magnetospheric research should be of great value in understanding astrophysical plasmas.

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TRITA-EPP-78-07

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April 1978, 16 pp, in English

Recent discoveries by means of in situ measurements have led to a substantial revision of our picture of the magnetosphere and parts of the heliosphere. This concerns such essential aspects as the character and distribution of electric fields and currents, the ways in which charged particles are energized, and the chemical composition of the magnetospheric plasma.

This revision reflects the fact that even in fundamental respects, real cosmical plasmas behave in different ways than predicted by the idealized models that have traditionally been used in magnetospheric physics as well as in astrophysics. The new understanding of the general properties of cosmical plasma that has been, and continues to be, provided by in situ measurements gives us a much improved basis on which to interpret astrophysical observations.

Key words: Birkeland currents, Chemical composition, Cosmic plasma, Electric currents, Electric fields, Frozen-in-magnetic field, Heliosphere, Magnetic merging, Magnetosphere, Parallel electric fields, Plasma, Reconnection, Structure of space.