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ELECTRODYNAMICS OF COSMICAL PLASMAS -
- SOME BASIC ASPECTS OF COSMOLOGICAL
IMPORTANCE

C.-G. Fälthammar

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

ELECTRODYNAMICS OF COSMICAL PLASMAS - SOME BASIC ASPECTS
OF COSMOLOGICAL IMPORTANCE

by

Carl-Gunne Fälthammar

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

ABSTRACT

In cosmology, as in astrophysics, the overwhelmingly dominant state of matter is the plasma state. Therefore it is necessary to take into account the properties of this state of matter, which in crucial respects are different from those of unionized matter. This paper reviews basic electrodynamic properties, as revealed by laboratory and space plasma experiments, and consequences of these. They include coupling between magnetic fields and the motion of matter, filamentary and cellular structure, anomalous momentum coupling and new mechanisms of chemical separation.

It is concluded that some of these properties, obviously important for the understanding of the present-day universe, must also have been important in the cosmological evolution of which today's universe is the result. As some of the crucial properties are still poorly understood, but being investigated by laboratory and space plasma experiments, the result of such experiments should also be very relevant to the development of cosmology.

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1. Introduction

In the present-day universe the completely dominant state of matter is that of plasma. This has far-reaching consequences for the understanding of astrophysical phenomena (Alfvén, 1977, 1981a, 1988; Fälthammar et al., 1978; Fälthammar, 1988a,b,c). The plasma state must have been as dominating in the past, too, and this must be taken into account in dealing with cosmological problems.

The most basic difference between ionized and non-ionized matter is the ability of carrying electric current. This ability is also the reason why virtually all the matter in the universe is - and presumably has always been - magnetized. The presence of the magnetic field has important dynamical consequences, since the magnetic force can locally be much greater than the gravitational force (§ 2).

The ability of carrying current, which is the basis for the magnetization, is a property that is still not well known in the case of cosmical plasma. It can be different by many powers of ten from what classical theories predict. In view of the crucial importance of electric current conduction in the cosmical plasma, it is discussed at some length (§3).

In laboratory and space plasmas electric currents tend to cause filamentation. Filamentary structures are also abundant in the cosmical plasma and make homogeneous models of astrophysical plasma very dubious. Correspondingly, homogeneous models are likely to be misleading when applied to cosmological processes (§ 4).

One of the notable characteristics of space plasma, revealed by satellites and space probes, is its tendency to form sharp boundaries between plasmas with different properties. This tendency toward "cellular structure" can have profound cosmological implications (§ 5).

A phenomenon called critical velocity interaction, first proposed in Alfvén's cosmogonic theory, has been observed in both laboratory and in space plasmas. It implies, among other things, an anomalous exchange of momentum between ionized and unionized matter (§ 6).

One of the surprising discoveries in the near-Earth plasma is the existence of previously unknown mechanisms which allow very efficient separation of different chemical species (§ 7).

As a result of space observations we now know that the behaviour of matter in space is rather drastically different from what could be expected from classical theory. The difference is due to previously unknown or disregarded plasma physical processes. Several of these processes - so important in the present-day universe - must also not be ignored in considering the cosmological evolution of which the present state of the universe is the result.

2. The magnetized plasma

Plasma, the ionized state of matter, which is rare in our close environment, is the dominating state in the universe as a whole. The sun and the stars as well as the diffuse matter between them, and between the galaxies, are all in this state despite their great differences in density and temperature. The only exceptions are the cold celestial bodies, such as the Earth and other planets, the satellites, asteroids, comets, meteoroids and dust grains, all of which together account for an extremely small fraction of the matter in the universe. Furthermore, all the cosmical plasma is magnetized. From the nearest cosmical plasma - the Earth's ionosphere - out to the most distant intergalactic regions all cosmical plasmas are penetrated by magnetic fields, which influence their physical properties in various, often dramatic, ways.

In diffuse matter, which forms a major part of the universe, the motion of each individual particle is strongly controlled

by the magnetic field. For example, a hydrogen ion in the solar wind with a thermal velocity of 20 km/s in the interplanetary magnetic field of 5 nT experiences a magnetic force of $1.6 \cdot 10^{-23}$ N which (at the Earth's orbit) is about 10^7 times stronger than the gravitational force from the sun. Even in the other extreme, e.g. in stellar interiors, where gravitational forces dominate, the magnetic field makes possible wave modes, such as Alfvén waves, that are not possible in unionized media. Some of the important consequences of the magnetic field will be discussed below.

The ever-present cosmical magnetic fields are not curl-free, except in very limited regions, such as certain environments of magnetized planets. That means that essentially all cosmical plasmas carry electric currents (Alfvén 1977, 1981a), which constitute the sources of the magnetic field.

Because of the key role played by the magnetic fields - and by the electric currents, without which they would not exist - it is obvious that the ability of the cosmical plasma to carry electric current is a property of crucial importance.

3. Classification of cosmical plasmas

Cosmical plasmas cover large ranges of density and temperature. However, in terms of many of their physical properties they can be classified into three broad categories on the basis of the mean free path, λ , in relation to gyroradius, ρ , and characteristic dimension, l_c (Alfvén and Fälthammar, 1963 §5.1) as follows

High density: $\lambda \ll \rho$

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

Low density: $l_c \ll \lambda$

High density plasmas prevail in stellar bodies, lower stellar atmospheres and lower planetary ionospheres. They are characterized by generally isotropic properties, except for Alfvén wave propagation. For example, high density plasmas are isotropic with respect to diffusion. Current densities and electric fields are related by a simple Ohm's law with a scalar conductivity.

Medium density plasmas are found in transition regions above the lower parts of stellar atmospheres and planetary ionospheres. They are characterized by anisotropic diffusion and current conduction. The relation between current density and electric field which also contains other quantities such as electron and ion pressure gradients and the relative velocity between the charged and the neutral components of the plasma (see e.g. Alfvén and Fälthammar, 1963, §5.2.3.2):

Under certain assumptions the generalized Ohm's law can be written in a form that looks just the same as the ordinary Ohm's law, except that the conductivity is now a tensor. The conductivity tensor reflects the fact that electric current is carried (much) more easily in some directions than in others. Thus an electric field in one direction usually produces a current in a different direction.

However, no matter how complicated the Generalized Ohm's law may be, it still represents a local macroscopic relationship, in the sense that the local electric field (together with local macroscopic properties of the plasma) determine the local current density uniquely. As we shall see, not even that need to be the case in a low density plasma.

Low density plasmas fill the rest of the universe, i.e. they

dominate planetary magnetospheres, the solar corona, interplanetary, interstellar and intergalactic space. They represent a very complicated state of matter that can entertain a host of waves and instabilities. Their electrodynamic properties are such that in general there does not even exist a local macroscopic relation between electric field and electric current density. For example, finite electric current may coexist with a zero electric field and vice versa. This means that the concept of conductivity as a local property becomes meaningless, and even remote parts of the current circuit must be taken into account .

A simple example is that discussed by Alfvén and Fälthammar (1963, §5.1.3), namely of electrons and ions trapped between two magnetic mirrors and having different angular distributions and hence differently distributed mirror points. Even if the total charge is zero, the electrons and ions contribute differently to the local charge density and hence they maintain an electric field without any net current. This example has been elaborated in greater detail by Whipple (1976). A case of experimentally observed magnetic-field aligned electric fields in a magnetic mirror with no electric current has been reported by Serizawa and Sato (1984).

4. The frozen field condition

The magnetic force provides a coupling between the electromagnetic fields and the dynamics of matter. This coupling is the basis of magnetohydrodynamics. One of the most widely used laws of magnetohydrodynamics is the law of "frozen in magnetic field". It applies if the electrical conductivity is sufficiently high, so that the magnetic Reynolds number, $\mu_0 \sigma l_C v_C$, is much greater than unity. (μ_0 is the permeability of vacuum in MKSA units, σ is the electrical conductivity, l_C the characteristic length and v_C the characteristic velocity.) As illustrated in Fig 1., this law means is that if two elements of matter are at some instant of time connected by a common magnetic field line, they remain thus connected at any later (or earlier) time, as long as the criterion of validity remains

satisfied throughout the region concerned. It is obvious that such a law greatly simplifies many magnetohydrodynamic problems, and has therefore been widely used. A simple example from astrophysics is the law of isorotation, which is a corollary to the law of frozen field lines. However, violation of the isorotation law seems to have played a crucial role in the cosmogonic process. In the cosmogonic theory of Alfvén and Arrhenius (1975) the structure of planetary and satellite systems is a result of isorotation being replaced by partial corotation (Alfvén 1981b).

In cosmical phenomena, the characteristic length l_c is usually so large that even conductivities that would seem moderate in Earthly contexts are easily sufficient to satisfy the criterion of large magnetic Reynolds number. However, Hannes Alfvén, who discovered the law, has warned against its uncritical use. The reason why caution is necessary is the complexity of current conduction in cosmical plasmas. As will be discussed in §3, classical formulas for the electrical conductivity of plasma are not always valid, and situations are not uncommon, where even the concept of conductivity becomes meaningless.

Violation of the law of frozen-in magnetic field, i.e. "cutting" of magnetic field lines requires that an electric field with a non-vanishing and non curl-free component along the magnetic field is established as illustrated in Fig. 2. For further explanation see Alfvén and Fälthammar (1963, § 5.4). Such components used to be considered impossible because they are in conflict with classical conductivity formulas. However, we now know that they are indeed possible for reasons to be discussed in §3.

The fact that the law of frozen-in magnetic field can be violated is important for the dynamics of the plasma, because it allows dynamical decoupling of magnetically connected plasma volumes. Through the magnetic-field aligned electric field that is a requisite for the violation it is also associated with energization of plasma particles.

5. Current conduction and magnetic-field aligned electric fields

The magnetic-field aligned electric fields that are required for violation of the frozen field condition, used to be discarded with the argument that they would be shortcircuited by the plasma, which in most cosmical contexts should (according to classical theory) have a high conductivity along the magnetic field.

As described above, current conduction in the real cosmical plasma can be much more complicated, especially in low density plasmas. As a result, magnetic-field aligned electric fields can indeed exist, and we now know, from satellite measurements of particles and fields in the Earth's magnetosphere, that magnetic-field aligned electric fields do exist there (and can have voltage drops of several kV).

As shown above, magnetic field aligned electric fields can in principle exist even without any net current, but they are particularly likely to occur if the plasma is forced to carry an electric current along the magnetic field. In that case there are three mechanisms that can allow magnetic-field aligned electric fields to exist without excessive current densities. There have been comprehensively treated by Fälthammar (1978) and will be only briefly mentioned here. A review of observational evidence was given by Fälthammar (1983)

(1) The magnetic mirror effect If a current flows out of a magnetic mirror in a low density plasma, only those electrons that are in the loss cone can contribute to the current. Provided the loss cone is kept filled by scattering in the source plasma, a simple relation holds between current density and the applied potential (Knight, 1973; Lemaire and Scherer, 1974, 1983; Fridman and Lemaire, 1980). If the mirror ratio is large, it can be shown that, there is a certain interval of intermediate current density, where this relation is linear, as illustrated in Fig 3 (Fälthammar, 1977). (This corresponds to a constant overall conductance, but a locally defined

conductivity does not exist.) This implies a quadratic relation between energy flux and potential drop. Precisely such a relation has been observed in precipitating auroral electrons as reported by Lundin and Sandahl (1978), Menietti and Burch (1981) and others. This makes it highly likely that the magnetic mirror effect is at least in some cases responsible for magnetic-field aligned potential drops above the aurora.

The relation also has the property that there is a saturation current that cannot be exceeded however large a voltage drop is applied (see Fig. 3). With insufficient scattering in the source plasma the current density is less than that given by the above-mentioned relation and can choke toward zero.

(2) Anomalous resistivity Current-driven instabilities may grow to such intensity that the motion of the current-carrying electrons is severely impeded. This creates an "anomalous resistivity", which according to theoretical estimates may exceed the classical one by many powers of ten. It has previously been invoked as responsible for magnetic-field aligned electric fields in the Earth's magnetosphere, but it is at present uncertain whether it really plays any major role.

(3) Electric double layers From laboratory experiments, as well as theory and numerical simulations, it is well established that current-driven instabilities can lead to an end state very different from the "turbulence" required for anomalous resistivity. This alternative end state is one or more electric double layers. A double layer is a potential structure with an extent along the current of only some tens of Debye lengths. The existence of the electric double layer has been well established in laboratory experiments. (For a review, see Torvén, 1979).

Numerous weak double layers have been observed in the Earth's magnetosphere, and it has been estimated that they may account for voltage drops of the order of kilovolts (Temerin et al., 1982; Mozer and Temerin, 1983) in agreement with a suggestion

by Block (1972).

There are reasons to believe that strong double layers (with kilovolt potentials in one step) may also exist, but these are very hard to observe directly, because of their small dimension. (In the ionosphere tens of Debylengths may be as little as a few meters.)

In the case of the magnetosphere it is likely that all of the above-mentioned mechanisms operate, but it is not yet known what their relative importance is.

In astrophysical and cosmological plasmas, too, these mechanisms should be important. There, it is even less known what role each of them plays. A couple of interesting suggestions may be mentioned. Alfvén (1978, 1981a) suggested that double radio sources may be the results of double-layer formation, Carlqvist (1986) considered double layers as a means of accelerating cosmic rays and Borovsky (1986) has suggested that they play a role in extragalactic jets. One or more of the mechanisms described above is needed to sustain the magnetic-field aligned electric field required for partial corotation, a key feature of the cosmogony of Alfvén and Arrhenius (1975). The partial corotation has been described by Alfvén (1981b).

Magnetic-field aligned electric fields will have the plasma dynamic consequence of violating the frozen field condition irrespective of which of the above mechanisms it is that supports them. They will also cause energization of charged particles, but in that respect they are very different depending on what the support mechanism is. For example, anomalous resistivity causes the ohmic power to be released mostly in the form of local heating. In the case of a double layer or magnetic-mirror supported field the released power is not deposited locally but carried away to be dissipated elsewhere. In the case of the Earth, magnetic field aligned electric fields thousands of km above the Earth energize electrons which carry their energy into the ionosphere, where

they deposit it to cause the aurora. Magnetic mirrors are common in the cosmical plasma and should very likely play a role as well.

6. Inhomogeneity - filamentation

From laboratory experiments it is well-known that current carrying plasma has a tendency to form filaments. We also know that filamentary structures are abundant in astrophysical plasmas. Examples among many are the solar corona, cometary tails, and interstellar nebulae. It has been suggested by Alfvén (1977, 1981a § II.4) that filamentation of astrophysical plasmas is also related to electric currents.

The inhomogeneity implied by the filamentation is important and means that cosmical plasmas are often very poorly represented by homogeneous models. The fact that this is true for present-day cosmical plasmas should be a strong warning against applying homogeneous models to the ancient plasmas that were protagonists in the cosmological process.

7. Cellular structure

One of the notable discoveries in the space plasma is the prevalence of sharply defined boundaries between plasma regions, often separating plasmas with different properties. Such boundaries are often marked by electric sheet currents. Examples are the magnetopause (cf. Fig. 4), the geotail neutral sheet and the solar wind "sector boundaries".

It has been pointed out by Alfvén (1981a, § II.10) that since - throughout the regions of space within the present reach of spacecraft - the cosmical plasma has this tendency toward dividing itself up into "compartments", it should have this tendency elsewhere, too. This has a very important

cosmological consequence, because a matter-antimatter symmetric universe may be possible, with matter and antimatter occupying separate "compartments" with too little interaction to be noticed (Alfvén, 1981a, § IV 9.6).

8. Critical velocity interaction

If a plasma and a neutral gas both are so thin that collisional momentum exchange is negligible, one would expect them to be able to move through each other without appreciable interaction. That this need not be so was suggested by Alfvén (1942) in his theory of the origin of the planets and satellites. He introduced the hypothesis that if the relative velocity exceeds a certain critical value, a strong interaction and rapid ionization of the neutral gas would take place. He further assumed that this "critical velocity", v_c , was given by the velocity at which the neutral-gas particles (mass M) have a kinetic energy equal to their ionization energy, eV_i :

$$\frac{Mv_c^2}{2} = eV$$

At the time this was proposed, there was no known reason why such a relation should hold. Nevertheless, the hypothesis was indeed confirmed later in a laboratory experiment (Fahleson 1961). For many years it remained a mystery, but dedicated experiments (Fig. 5) have now clarified the phenomenon at least in general terms. What is involved is an instability that transfers energy from ions to electrons, so that they become capable of ionizing. However, important questions still remain (Brenning and Axnäs, 1988).

In the meantime the phenomenon has been observed also in the space plasma (Haerendel, 1982). For a recent review of space experiments on this phenomenon see Torbert (1988).

The phenomenon has been invoked in a number of cosmical applications, such as the formation of an ionosphere at the Jovian satellite Io (Cloutier, 1978), the interaction of the solar wind with gas clouds (Lindeman et al., 1974; Gold and Soter, 1976), with comets (Haerendel, 1986; Galeev et al., 1986), with planetary atmospheres (Luhmann 1988) and with the interstellar medium (Petelski et al., 1980; Petelski, 1981). Thus, the phenomenon may have important astrophysical implications. However, these cannot be evaluated in detail until a full understanding of the phenomenon has been achieved, which is the goal of rocket experiments now being prepared.

The fact that the existence of this anomalous interaction has been so definitely documented plus the fact that it has been so successfully applied to the cosmogonic process, should make it interesting to keep in mind in cosmological contexts, too.

9. Chemical separation

Another discovery of profound astrophysical, and presumably also cosmological, significance was made in the Earth's magnetosphere only about a decade ago. Until then it had been assumed as a matter of fact that the plasma populating the magnetosphere (except the very closest parts) was a hydrogen plasma from the sun (delivered to the magnetosphere by the dif-solar wind). When the appropriate in situ measurementss were made, it was found that in large parts of the magnetosphere the major consituent is sometimes oxygen plasma from the Earth's own ionosphere. This is so because in magnetically disturbed times, when strong electric currents flow between the Earth and outer space, large amounts of ionospheric oxygen ions are expelled into the magnetosphere. The complex exchange of matter as we now know it is illustrated in Fig. 6.

This expulsion of ions is highly selective. Therefore, the ions that reach the magnetosphere have a chemical composition very ferent from the one prevailing where they came from. This

constitutes a very efficient chemical separation mechanism, which was entirely unknown and unexpected until it was empirically discovered in the magnetosphere. It is hardly necessary to say that this has great potential implications on the interpretation of abundance ratios in cosmical plasmas.

10. Concluding remarks

Discoveries made by in situ observations in the space plasma have drastically changed our concept of how cosmical plasma behaves. This should have profound implications not only for our understanding of the astrophysical phenomena in today's universe, but also of the cosmological processes of which this universe is the result.

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Fig. 1. The law of "frozen-in magnetic field" implies that if two elements of plasma are connected by a common magnetic field line at some instant t_1 , they are thus connected at any other instant t_2 , regardless of how much the magnetic field has been deformed.

Fig. 2. Magnetic-field-aligned electric field components ($E_{||}$) with a non-vanishing curl can violate the "frozen-field" condition and allow plasma elements on a common magnetic field line to move (by $E \times B / B^2$ -drift) differently.

Fig. 3. Example of current voltage relation for a low density plasma (after Fälthammar, 1977)

- Qualitative characteristics
- Quantitative relations for plasma in arroral magnetic field lines

Fig. 4. The richly structured plasmas of the magnetosphere have brought profound new insights into the properties of cosmic plasmas. The magnetopause was the first example of the tendency of cosmic plasmas to form cellular structures. As suggested by Alfvén (1981a) cellular structure may allow a matter-antimatter symmetric universe.

Fig. 5. The critical velocity phenomenon, successfully invoked in Alfvén's (1942) cosmogonic theory allows plasma and neutral gas to interact very strongly even when no interaction is expected according to classical theories. The figure shows the sudden braking of a supercritical plasma flow in a laboratory experiment (Brenning and Danielsson, 1975).

Fig. 6. Schematic overview of sources, transport and acceleration of plasma in the magnetosphere according to Collin et al. (1984).

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

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Keywords: Cosmology, Plasma, Electrodynamics