# THE PLASMA UNIVERSE

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## ABSTRACT

The term "Plasma Universe", coined by Hannes Alfvén, emphasizes the fact that plasma phenomena discovered in the laboratory and in accessible regions of space, must be important also in the rest of the universe, which consists almost entirely of matter in the plasma state.

Relevant aspects of this concept will be discussed. They include the response of the plasma to electric currents, the support of magnetic-field aligned electric fields, violation of the frozen-field condition, rapid release of magnetically stored energy, acceleration of charged particles, chemical separation, filamentary and cellular structures, and critical velocity interaction.

## 1. Introduction

The term Plasma Universe was coined by Hannes Alfvén (1986) to be the symbol of a change of paradigm (Alfvén 1983), resulting from progress in plasma physics, and especially from new empirical knowledge gained by in situ measurements in space plasmas.

It is a well known fact that almost all the matter that constitutes our universe is in the plasma state. Virtually all astrophysical phenomena take place in a plasma environment, and many of them are of an essentially plasma physical nature.

Exciting discoveries are being made by means of modern remote sensing techniques using formerly inaccessible parts of the electromagnetic spectrum. The phenomena behind them involve matter in various extreme plasma states. Translation of such observations into understanding of the physics of the phenomena involved has to rely on whatever knowledge we have of how matter behaves in the plasma state.

In building the necessary foundation of knowledge, the empirical knowledge so far gained - and that which is still to be gathered - in laboratories and in the Earth's own magnetosphere plays a crucial role.

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To fully recognize the role of such empirical knowledge of plasmas, it is useful to briefly look back at the evolution of plasma physics.

## 2. Classical versus modern plasma physics

The evolution of plasma physics falls into two distinct epochs, which we may characterize by the terms classical and modern plasma physics. Classical plasma physics was based on a very limited empirical basis derived essentially from experiments with cool, weakly ionized plasmas. On this slim empirical basis was built an comprehensive theoretical superstructure. This classical plasma theory was assumed to have general validity, i. e. to be applicable to parameter ranges that had not yet been attained experimetally.

From the classical plasma theory, applied to extremely hot plasmas, such as are needed for producing thermonuclear fusion energy, it was in the 1950's generally concluded that the problem of magnetic confinement of hot plasma was rather simple.

As soon as the thermonuclear effort made it possible to conduct experiments in the new parameter range of very hot plasmas, the limited validity of the classical plasma theory became evident. A number of "anomalous" phenomena, not foreseen in the framework of classical theory, were found. The resulting "thermonuclear crisis" led to the start of a new era in thermonuclear research. The lesson learned was that even self-consistent, sophisticated and elegant theories can be completely misleading unless based on sufficient empirical knowledge. Therefore, the new era in in thermonuclear research is characterized by a close interplay between experimental and theoretical efforts.

Thus, by making available a new parameter range for empirical study, the thermonuclear effort became one of the foundations of modern plasma physics.

The other foundation was the space effort, which made it possible to make in situ measurements, and even active experiments, in the space plasma. This led to an even more drastic widening of the parameter ranges in which empirical knowledge can be gained.

Like in the case of fusion research, there are lessons to be learned from the way in which magnetospheric research developed. In this case too, some generally accepted theoretical deductions turned out to be misleading. In retrospect we know that the reason was that relevant plasma physical processes were in some cases known but disregarded, in other cases not yet discovered.

## 3. The metamorphosis of the magnetosphere

The magnetosphere as we now know it (Fig. 1) is very different from the simple concepts of it that prevailed before the space age.

The pre-space age concepts of our neighbourhood in the cosmos were based on generally accepted classical theories, which were

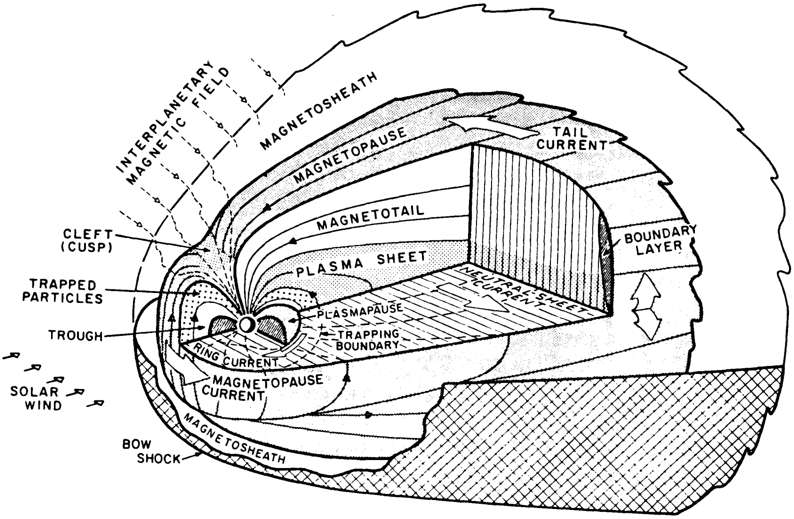

Fig. 1. The Earth's magnetosphere as we now know it. This dynamic and richly structured cosmical plasma system provides a unique opportunity of laying a safer empirical foundation for understanding more distant cosmical plasmas.

believed to be generally valid. On this basis it was concluded that the electric field would be a secondary parameter of little relevance. As a consequence, electric fields, and in particular magnetic-field aligned electric fields, which we now know to be of crucial importance, were long disregarded.

Much of this delay could have been avoided, if certain results already known from laboratory experiments had been applied to the space plasma. For example, Hannes Alfvén proposed already in 1958 that electric double layers, a phenomenon that had been observed in the laboratory, could exist above the ionosphere and cause energization of auroral primary electrons (Alfvén 1958). This suggestion, now known to be valid, was almost universally refuted because it was incompatible with generally accepted theories.

One more example may be quoted, since it has obvious repercussions in astrophysics. Quite late in the space age, it was discovered that, over the auroral oval, there are veritable fountains of upflowing ionospheric ions. Indeed, the outflux is so great that at certain times large parts of the magnetosphere is dominated by ionospheric ions, i. e. by matter terrestrial - not solar - origin. Furthermore, the most prevalent ion is usually O+, in spite of the fact that the upper ionosphere contains much more He+ and H+. In other words, the ionospheric ions that populate the magnetosphere can have a chemical composition very different from the composition of the underlying ionosphere. This is the result of a completely unexpected, and still not fully understood, chemical separation processes that operates in the space plasma.

Thus, serious misconceptions about the near space plasma prevailed until the appropriate in situ measurements were made and revealed a very different reality.

The reason for the difference is that the real magnetosphere is controlled by complex plasma processes that were either neglected or not yet discovered.

Since those neglected or undiscovered plasma processes make such a great difference in our little corner of the universe, no doubt they must also make great differences in the rest of the universe, where they still remain to be applied (Fälthammar et al. 1978). Judging by the metamorphosis of the magnetosphere, what is to be expected in astrophysics may be no less than a change of paradigm, as predicted by Alfvén.

In the rest of this paper we shall discuss some of the plasma phenomena that are now known to play a role in our own corner of the Plasma Universe.

## 4. Electric currents in cosmical plasma

Except in very limited regions, for example parts of planetary environments, the magnetic field is not curl-free. This means that in almost all cosmical plasmas the existence of the magnetic field depends on currents that flow in the plasma itself. This means that the ability of the plasma to carry electric current is essential, and we now know that this ability can be much more limited than classical theory would predict. It is therefore important to explicitly account for the currents (Alfvén 1977).

## 5. Current limitation and magnetic-field aligned electric fields

### Anomalous resistivity

The first widely recognized mechanism for radically changing the current-conducting capability of a plasma was anomalous resistivity. Current-driven instabilities were assumed to drive microinstabilties that developed to a state of microturbulence with electric fields large enough to reduce the mobility of the conduction electrons by several powers of ten.

This phenomenon was invoked in explaining a number of phenomena, such as acceleration of auroral particles and dissipation in singular regions where MHD breaks down. However, in the light of direct measurements it is doubtful whether anomalous resistivity, plays any significant role in the magnetosphere (Coroniti 1985).

To determine whether or not anomalous resistivity is important in astrophysical plasmas, we need to understand much better than now the nonlinear development of the instabilities concerned. Laboratory experiments and observations in the space plasma combined with numerical simulations may provide the required insights.

## Electric double layers

From laboratory experiments it is known that current-driven plasma instabilities may lead to a completely different end state than anomalous resistivity , possibly with anomalous resistivity as a transient intermediate state (Bohm and Torvén 1987). This alternative end state is a state with one or more double layers (for a recent review, see Raadu 1989).

Electric double layers in non-magnetized plasma have been known from the time of Langmuir in the beginning of this century. However, their existence in magnetized plasmas was proved experimentally as late as 1978 (Coakley et al. 1978; Torvén and Anderson 1979). Unlike anomalous resistivity, which, if it exists, allows the plasma to support a distributed potential drop, the electric double layer is a higly localized potential structure with a thickness of only tenths of Debye lengths. A classical case of such a structure observed in the laboratory is shown in Fig. 2.

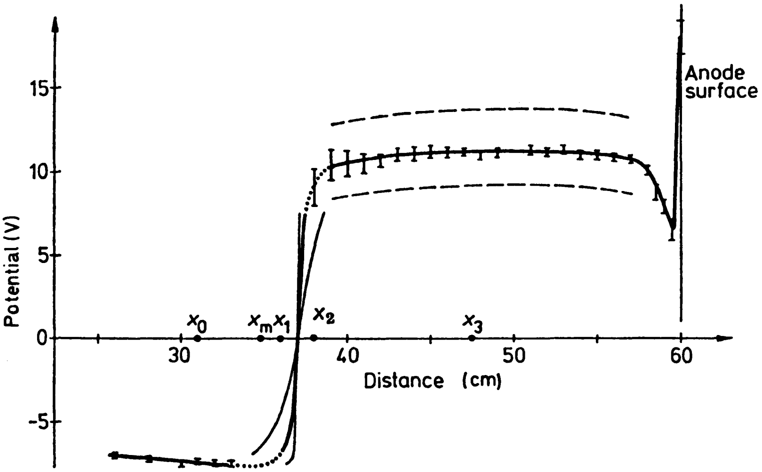

Fig. 2. Example of a strong electric double layer observed in the laboratory (Torvén and Lindberg 1980). Formation of electric double layers can drastically change the properties of a plasma in terms of its ability to (1) carry electric current, (2) accelerate charged particles and (3) release magnetically stored energy.

In the laboratory, the consequences of double layer formation depend on the curciut of which it is an element. In a low inductance circuit, the current is disrupted. In a high inductance circuit, large overvoltages are created, and the continued flow of current through these voltages rapidly drains the magnetic energy in the circuit (Torvén et al. 1985). Situations corresponding to both these cases are conceivable in cosmic plasmas.

There also exist electric double layers without any net current. The simplest example is the wall sheath of a plasma column.

Based on an overwhelming body of evidence (for a review see for example Fälthammar 1983) there is now an almost complete consensus among space physicists that electric double layers play an important role in auroral particle acceleration.

Electric double layers have also been invoked to explain phenomena in various astrophysical plasmas. A few examples may be mentioned.

The first suggestion that strong double layers may be responsible for the rapid release of magnetically stored energy that takes place in solar flares was made by Jacobsen and Carlqvist (1964). The idea was further developed by Alfvén and Carlqvist (1967), Carlqvist (1969, 1986) and Hasan and ter Haar (1978).

In the context of X-ray pulsars it has been suggested that an electric double layer is established in the accreting matter (Williams et al. 1986). In this case it is a double layer with no net current.

The possibility of electric double layers being responsible for the huge energy release in so-called double radio sources has been suggested by Alfvén (1978). In a detailed study of this idea Borovsky (1986) suggests that both electric double layers and anomalous resistivity exist, in a kind of symbiotic relation, in the extragalactic jets associated with the double radio sources.

Acceleration of charged particles to cosmic ray energies has been suggested by Alfvén (1978). In an analysis of relativistic double layers, Carlqvist (1986) has estimated that double layers may allow acceleration of up to $10^{14}$ eV per unit charge.

A thorough treatise on electric double layers and their role in astrophysics has recently been given by Raadu (1989).

## The magnetic mirror effect

In a collisionless plasma there is a third mechanism by which electric currents can be limited and magnetic-field aligned electric fields supported, namely the magnetic mirror effect. (For a systematic discussion of these mechanisms, see Fälthammar, 1978.) For a current flowing out of a magnetic mirror, the most important carriers of the current, namely the electrons, are impeded by the magnetic mirror force, and only those in the loss cone can contribute to the current. Under certain assumptions, one of which is continual replenishment of the loss cone, there exists a simple relation (Knight 1973; Fridman and Lemaire 1980) between the current density in the mirror neck and the total applied voltage. One feature of the relation is that there exists a saturation current density that cannot be exceeded however large voltage is applied.

In some cases, observed with the Viking satellite this saturation seems to have been reached (Brüning et al. 1989).

In the case of the Earths auroral oval the relation has a linear part which corresponds to a constant conductance of typically 3 ($\mu$A/m$^2$)/kV (Fälthammar 1977), in good agreement with observations.

If the scattering in the source plasma is insufficient to keep the loss cone filled, the Knight relation becomes invalid, and the current can choke to arbitrarily small values.

It is well established that the magnetic mirror effect plays an important role in the magnetosphere. Since inhomogeneous magnetic fields are common in astrophysical plasmas, this effect may well be important there, too.

### Violation of the frozen-in field condition

The existence of magnetic-field aligned electric fields means that the frozen-in magnetic-field condition can be violated (see e.g. Alfvén and Fälthammar 1963, Ch. 5.4.1). Such violation has been well established in the magntosphere, and may be important in other parts of the universe, wherever one or more of the three above-mentioned mechanisms operate.

One example where unfreezing of magnetic field lines is invoked is in Alfvéns theory of the saturnian rings. In this theory, unfreezing is a requisite for the so-called partial corotation (Alfvén 1981, Ch. III.3).

## 6. Filamentary structure

From the laboratory it is well known that current-carrying plasma has a tendency to break up into filaments.

In the magnetosphere the most conspicuous example of filamentary structure is that of the aurora. Unfortunately, direct measurements of electric currents in the space plasma are not yet possible, and the only information available is that deduced from single-satellite measurements of the magnetic field. Therefore the exact relation between auroral currents and auroral filamentation remains to be determined.

A theoretical relation applicable to the filamentation problem, in the presence of magnetic, gravitation and pressure forces, has been derived by Carlqvist (1988). It includes the Bennett relation and Jeans' criterion as special cases.

## 7. Cellular structure

One of the surprising discoveries in the space plasma is the prevalence of sharply defined boundaries between plasma regions, often regions with different properties such as density, temperature or composition. Such boundaries are often marked by electric sheet currents. Examples are the magnetopause, the geomagnetic neutral sheet and the solar wind "sector boundaries".

It has been pointed out by Alfvén (1981, Ch II.10) that the cosmical plasma thus has a tendency toward dividing itself up into "compartments". As this tendency has been found to be present throughout the regions of space that happen to be within the reach of spacecraft, it would be surprising indeed, if it did not also exist throughout the cosmical plasma. If it does, one important consequence is that a matter-antimatter symmetric universe may be possible, because matter and antimatter may occupy different "compartments", separated by "Leidenfrost layers" (Alfvén 1981, Ch IV 9.6).

## 8. Chemical separation

One of the great surprises in magnetospheric research was the discovery of large outflows of oxygen ions from the ionosphere and of the fact that large regions of the magnetosphere are sometimes dominated by oxygen plasma that has originated in the Earth's own atmosphere (see e.g. Chappel et al., 1987 and references therein).

One reason why auroral currents cause an exchange of matter is that they can drive instabilities, which cause transverse acceleration of ions. As a consequence of their increased orbital magnetic moment these ions are expelled into the magnetosphere by the magnetic mirror force (see e.g. Kaufmann, 1984 and references therein).

This energization and subsequent expulsion of ions is highly selective. Therefore, the ions that reach the magnetosphere have a chemical composition very different 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. This has great potential implications on the interpretation of abundance ratios in astrophysical plasmas.

## 9. The Critical Velocity phenomenon in plasma neutral-gas interaction

Alfvén's (1942) theory of the origin of planets and satellites (Alfvén and Arrhenius 1976) was based on the hypothesis that a plasma and a neutral gas in relative motion experience a strong interaction (and a violent ionization of the neutral gas), if the relative velocity exceeds a certain critical value, even if binary collisions are entirely insufficient for any appreciable momentum exchange. The value of this critical velocity was assumed to be the one where the kinetic energy of the plasma ions, in the rest frame of the neutral gas, equals the ionization energy of the latter. This hypothesis had no support whatsoever in the physics known at time it was invoked. Nevertheless, its validity was discovered in a laboratory experiment by Fahleson (1961) and later confirmed in many other experiments.

Thanks to dedicated laboratory experiments (for reviews see Sherman 1977 and Raadu 1978), the phenomenon is largely understood but important unsolved problems remain (Brenning and Axnäs, 1988). The phenomenon has also been found to operate in the space plasma.A recent review of space experiments on the phenomenon has been given by Torbert (1988).

The Critical Velocity phenomenon has been invoked in a number of cosmical applications, such as the formation of an ionosphere at the Jovian satellite Io (Cloutier et al., 1978), the interaction of the solar with gas clouds (Lindeman, 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). Thus, the phenomenon may have important astrophysical implications, but these cannot be evaluated in detail until a full understanding of the phenomenon has been achieved.

## 10. Concluding remarks

Discoveries made by in situ observations of the near Earth space plasma has necessitated dramatic revisions of our concept of how cosmic plasmas behave. The reason for the unexpected behaviour is plasma processes that were previosly either neglected or not yet known. As our universe, like the Earth's space environment, consists almost entirely of plasma, drastic revisions of astrophysics, too, may be needed before we have a true concept of our Plasma Universe.

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