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Contents

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, and filamentary and cellular structures.

1. Introduction

The term Plasma Universe was coined by Hannes Alfvén (1986) to be the symbol of a change of paradigm (Alfvén 1983) in astrophysics as well as in cosmology and cosmogony. This change is necessitated by progress made in modern plasma physics, and especially by the empirical knowledge provided 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. Yet, the implications of this dont seem to be widely recognized.

Exciting astrophysical 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. They occur in regions that are forever inaccessible to in situ measurements. 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. If this knowledge is incomplete or incorrect, the remote sensing observations may fail to enhance our knowledge and may even delay progress by strengthening our misconceptions.

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 Earths own magnetosphere plays a crucial role.

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 impressive theoretical superstructure with a highly sophisticated mathematical formalism. 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 fuel was rather simple, and that thermonuclear fusion energy could become a reality in about 15 years. Large projects with this goal were started, and technical capabilities were created that allowed generating much hotter plasmas than before.

As soon as this 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 theories, however self-consistent, sophisticated and elegant, 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 a highly complex plasma system and 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, like in the case of fusion, were beleived to be generally valid. The theoretical predictions about space around us were therefore beleived to describe the real world.

On the basis of classical conductivity formulas it was assumed that the space plasma, and indeed most cosmical plasmas, should have negligible resistivity. This allowed the use of idealized magnetohydrodynamic models, from which it was concluded that the electric field would be a secondary parameter of little relevance, and that magnetic-field-aligned, often called "parallel", electric fields were impossible. Therefore, electric fields, and in particular magnetic-field aligned electric fields, which we now know to be of crucial importance, were long disregarded. Even today, only a few space missions in the outer magnetosphere have included measurements of electric fields.

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. Alfvén and collaborators proposed double layers to explain the energy release in sclar flares (Jacobson and Carlqvist 1964; Alfvén and Carlqvist 1967). This suggestion met a similar response, but has, decades later, become fashionable, even to the extent that one of the Alfvén-Carlqvist papers will be presented as a Citation Classic in the next issue of Current Contents.

In magnetospheric physics, too, there are too many examples of how mathematically elegant theories have misled the scientific community for decades. The work of Störmer in the beginning of the century was condemned in favour of the theories of Chapman until <u>in situ</u> observations in space forced the community to accept that it was the physical insights of Störmer and not the mathematical elegance of Chapman that correctly described reality.

One more example may be quoted, since it has obvious repercussions in astrophysics. Nearly two decades into the space age it was almost universally assumed that the material content of the magnetosphere was a hydrogen plasma from the sun. But as soon as suitable particle detectors looked downward from satellites, it was discovered that, over the auroral oval, there are veritable fountains of upflowing ionospheric ions. Indeed, the outflux is so great that at times large parts of the magnetosphere is dominated by ionospheric ions, i. e. by matter originating in the Earths own atmosphere. It has even been suggested that essentially all the matter in the magnetosphere is of terrestrial - not solar - origin (Chappell et al. 1987). Furthermore, the most prevalent ion is usuallu 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 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. Almost certainly we have not yet discovered all the relevant plasma processes that control the physics of our own magnetosphere.

What this means is that (1) even as late as a few years ago, our understanding of plasmas was still poor enough to allow fundamental errors in our description of the Earths own environment, and that (2) even today and a posteriori we cannot fully explain certain facts of fundamental importance, for example the differences in chemical composition between two so closely coupled systems as the ionosphere and the magnetosphere.

All this should inspire great caution in making statentements about more distant astrophysical plasmas. If 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. If the metamorphosis of the magnetosphere is any guide, what is to be expected in astrophysics should be no less than a change of paradigm, as predicted by Alfvén.

As our understanding of cosmical plasmas still is incomplete, we do not know exactly what the new paradigm will be like. But certainly it must build heavily on the basically electrical processes that make the plasma state of matter so different. Therefore, plasma phenomena, those known and those not yet discovered, must play an often dominating role alongside the physical processes traditionally taken into account.

Some of the plasma phenomena that we already know to play a role in the nearby space plasma will be discussed below.

4. Electric currents in cosmical plasma

Cosmical plasmas are, virtually without exception, magnetized. While the importance of the magnetic field itself has been generally recognized, the same is not true for the electric currents, without which the magnetic fields would not exist. In idealized magnetohydrodynamics, which is often applied to cosmic plasmas, there is no need to consider the current per se, because the plasma, assumed to be infinitely conductive, is expected to accomodate any current required to sustain whatever magneic field comes out of the equations. Hannes Alfvén (1977) has emphasized that in a real plasma this approach is dangerous, and it is important to explicitly account for the currents.

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.

When a plasma is forced to carry electric current, its properties can change in important ways. Instabilities driven by the current can drastically reduce the plasmas ability to carry electric current and correspondingly enhance its ability to sustain electric fields. Other current-driven instabilities may be responsible for the above-mentioned chemical separation in the magnetosphere. Both these consequences of electric currents will be discussed below.

More generally, Alfvén has suggested that plasmas can be broadly divided into two main categories, passive and active plasmas. The passive plasmas are those which do not carry any appreciable currents. They are quiet and comparatively simple to describe theoretically. The active plasmas, drawing energy from the current that they carry, are characterized, on both microscopic and macroscopic scales, by a dynamic and complicated behaviour, which is hard to predict theoretically or even explain *a posteriori*.

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 the so-called 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 result was based on the assumption that the end state of the nonlinear development would be one of homogeneous microturbulence.

Not untypically this phenomenon was then invoked in explaining a number of phenomena, such as acceleration of auroral particles and dissipation in singular regions where MHD breaks down. Measurements in the Earths neutral sheet have been interpreted to support the existence of anomalous resistivity there (Cattell and Mozer 1982), but on the whole direct measurements have reduced the prospects for anomalous resistivity, and it is doubtful whether it plays any significant role in the magnetosphere (Coroniti 1985).

For laboratory plasmas the experimental evidence of anomalous resistivity seems to be inconclusive. At least one case of current limitation originally ascribed to anomalous resistivity has been proved to be due to an entirely different phenomenon, the electric double layer described below (Torvén 1978). A state that appears similar to anomalous resistivity also seems to occur as a transient state leading to double layer formation (Torvén 1987).

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 (although possibly with anomalous resistivity as a transient intermediate state). This alternative end state is a state with one or more double layers.

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 (Torvén and Anderson 1978, 1979; Coakley et al. 1978). 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 some tenths of Debye lengths. A classical case of such a potential structure observed in the laboratory is shown in Fig. 2. Even in the laboratory, the double layer is difficult to study in detail because of its rapid motions and time variations. The instantaneous potential profile depicted in Fig. 2 was possible to obtain by a dual coincidence technique.

The example shown in Fig. 2 is a strong double layer, *i. e.* one where the voltage drop is much larger than the voltage equivalent of the electron temperature of the surrounding plasmas. The opposite is true for weak double layers, which are also known to exist. For natural reasons, the interest in cosmical applications has mainly been attached to strong double layers, but recent discoveries in the magnetosphere have brought also weak double layers into focus.

Many questions still remain concerning the formation and properties of double layers. The double layer is a higly non- linear phenomenon which is not easily accessible to theoretical analysis. The best hope of investigating it is by a combination of laboratory experiments and numerical simulation.

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. Situations corresponding to both these cases are conceivable in cosmic plasmas.

For completeness it should be mentioned that there also exist electric double layers without any net current. The simplest example is the wall sheath of a plasma column.

For many years now, there has been an almost complete consensus among space physicists that electric double layers play an important role in auroral particle acceleration. This is based on an overwhelming body of circumstantial evidence (for a review see for example Fälthammar 1983), while the direct observations of double layers are scarce.

The nowadays conventional concept of auroral double layers is completely in agreement with Alvéns (1958) suggestion. It is illustrated schematically in Fig. 3

One of the most direct indications of a magnetic-field aligned potential drop above the auroral ionosphere comes from a rocket experiment illustrated in Fig. 4. An artificial Ba+ cloud ejected upward along a magnetic field line experienced a sudden acceleration corresponding to a potential drop of 7.2 kV. The observation can only give an upper limit to the spatial extent of the potential drop, but the most likely explanation of the potential drop is a strong double layer. As the double layer is only some tens of Debyelengths thick, the probability of hitting it with a satellite is small, and only very few such encounters have been reported (Mozer et al. 1980). More recent observations attributed to double layers have been made with the Swedish satellite Viking. An example is shown in Fig. 5. The observed spatial variation of the electric field is interpreted in terms of a passage through a structure such as in Fig. 3. The electric field points inward from both sides toward the centre of the structure, where the potential is about 0.7 kV negative relative to the surroundings.

Weak double layers above the aurora were first reported by Temerin et al. (1982) on the basis of electric field data from the satellite S3-3. An example is shown in Fig. 6. The magnetic-field aligned component of the electric field exhibits a number of small wiggles interpreted as solitons (with no net potental across them) and double layers with a net potential drop of a fraction of a volt. The reason these structures can be observed is that they are so numerous and encounter the satellite in their rapid motion along the magnetic field. In fact, they are so numerous that in spite of the small potential drop across each of them, it is estimated that they may account for an accumulated potential drop in the kilovolt range (Mozer and Temerin 1983). This conclusion has been confirmed by later measurements on the Viking satellite (Boström et al. (1987).

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). It is interesting to notice that even the concept of multiple weaker double layers has been invoked in this context (Hénoux 1986).

In the context of X-ray pulsars, assumed to be neutron stars, 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 (1977, 1978). In a more 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). Unipolar dynamo action of rotating galaxies are assumed to drive electric current systems with 10^{17} - 10^{19} A, in which pinching and filamentation create conditions for formation of double layers (Alfvén and Carlqvist 1978). In a detailed 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 of the physics of electric double layers 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. In the case of the currents from the Earths auroral oval, the relation is as illustrated in Fig. 7. Note that (1) there is a saturation current density that cannot be exceeded however large voltage is applied and (2) in this particular case the relation is linear over about three powers of ten .

The linear part of the characteristic corresponds to a constant conductance, which in the case of the Earths auroral oval a typical value of 3 (uA/m2)/kV (Fälthammar 1977). This is in good agreement with the typical current densities and voltage drops above the aurora. Unlike the conductance, the concept of conductivity has no meaning in this case.

The linear relation between current density and electric potential drop implies a quadratic relation between voltage drop and precipitated power. Taking the voltage drop to be given by the energy of the precipitating electrons, Lundin and Sandahl (1978) found an excellent agreement with observations, as illustrated in Fig. 8. This is convincing evidence that in this case the magnetic mirror force was responsible for maintaining the potential drop required to accelerate the electrons.

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

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

Violation of the frozen field condition

The existence of magnetic-field aligned electric fields means that the frozen magnetic-field condition can be violated. This means that magnetically connected plasma regions can move independently of each other. 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), which very accurately accounts for some of the key structures in the rings.

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. We also know that magnetic-field aligned currents are important in the auroral process. In the magnetospheric equatorial plane filamentary currents on the scale of 90-200 km have been identified by Robert et al. (1984).

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. This situation may be improved with the launch of the cluster satellites, which for the first time will make systematic multi-point measurements in the magnetosphere. Until then the exact relation between auroral currents and auroral filametation will remain uncertain. A theoretical relation applicable to this problem has been derived by Carlqvist (1988). This very general relation includes the Bennett relation and the Eddington relation 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 (1981a 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 this tendency 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 1981a, Ch IV 9.6).

8. Chemical separation

It was suggested by Block and Fälthammar (1969) that the interaction of auroral electric currents with the ionospheric plasma that is forced to carry them should lead to an exchange of plasma between the ionosphere and the outer magnetosphere. Nevertheless, 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. Shelley et al., 1982; Shelley, 1986; Collin et al., 1984; Chappel et al., 1987 and references therein).

One reason for the exchange of plasma between the ionosphere and the magnetosphere is that pointed out by Block and Fälthammar (1969). Another, related mechanism, operating at the magnetospheric end of the magnetic field line has been described by Atkinson (1984).

A third 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. It is hardly necessary to say that this has great potential implications on the interpretation abundance ratios in astrophysical plasmas.

Still another possible mechanism of chemical separation in cosmical plasmas has been studied by Marklund (1979).

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

Alfvén's (1942) theory of the origin of planets and satellites 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. An example is shown in Fig. 9. A thin plasma moving at supercritical speed encounters a thin neutral gas cloud located around z = 0. Although momentum exchange by binary collisions is negligible, the plasma is suddenly decelerated to the critical velocity and the neutral gas subject to violent ionization. A condition for this to happen is the presence of a magnetic field with a component transverse to the relative motion.

Thanks to dedicated laboratory experiments the phenomenon is largely understood (Sherman, 1973; Raadu, 1978). A bibliography as of 1982 has been compiled by Axnäs et al. (1982). However, important unsolved problems remain (Brenning and Axnäs, 1988). The phenomenon has also been found to operate in the space plasma (Haerendel, 1982 ; Newell, 1985; Brenning et al., 1988a; Brenning and Axnäs, 1988; Lai and Murad, 1989). A recent review of space experiment 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, 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; Petelski, 1981). 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

Earths environment, consists almost entirely of plasma, drastic revisions of astrophysics, too, may be needed before we have a true concept of our Plasma Universe.

Captions to the figures

Fig. 1. The magnetosphere of the Earth is a dynamic and richly structured plasma system. Its properties are thouroughly different than expected - a result of plasma processes that were previously either neglected or not yet discovered.

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

Fig. 3. Conceptual sketch (not to scale) of electric equipotentials associated with a strong electric double layer on an auroral magnetic field line.

Fig. 4. Artificially injected cloud of Ba+ ions on an auroral field line (Haerendel 1976). The sudden change of slope represents a velocity change corresponding to 7.2 keV, apparently caused by a potential drop of 7.2 kV.

Fig. 5. Electric field structure observed with the Swedish satellite Viking above the auroral oval (Fälthammar et al. 1987).

Fig. 6. Electric field components transverse and parallel to the Earths magnetic field above the auroral oval (Mozer and Temerin 1983). The parallal component (bottom graph) shows signatures of solitons and double layers (marked DL).

Fig. 7. Relation between magnetic-field aligned electric current density and applied voltage difference in a low density plasma (Fälthammar 1977). (a) Qualitative representation of the relation (linear scales) (b) Quantitative example for the Earths auororal oval (logarithmic scales) Note the existence of (1) a nearly linear part of the characteristic and (2) a saturation current density that cannot be exceeded.

Fig. 8. Comparison between accelerating voltage and energy flux shows a very good agreement with a quadratic relation, as expected for a potential drop supported by the magnetic mirror force (Lundin and Sandahl 1978).

Fig. 9. Experimental confirmation of the critical velocity phenomenon. A magnetized plasma moving at supercritical speed is rapidly decelerated to subcritical speed as it encounters a neutral gas cloud, in spite of negligible momentum exchange by binary collisions (Brenning and Danielsson 1975).

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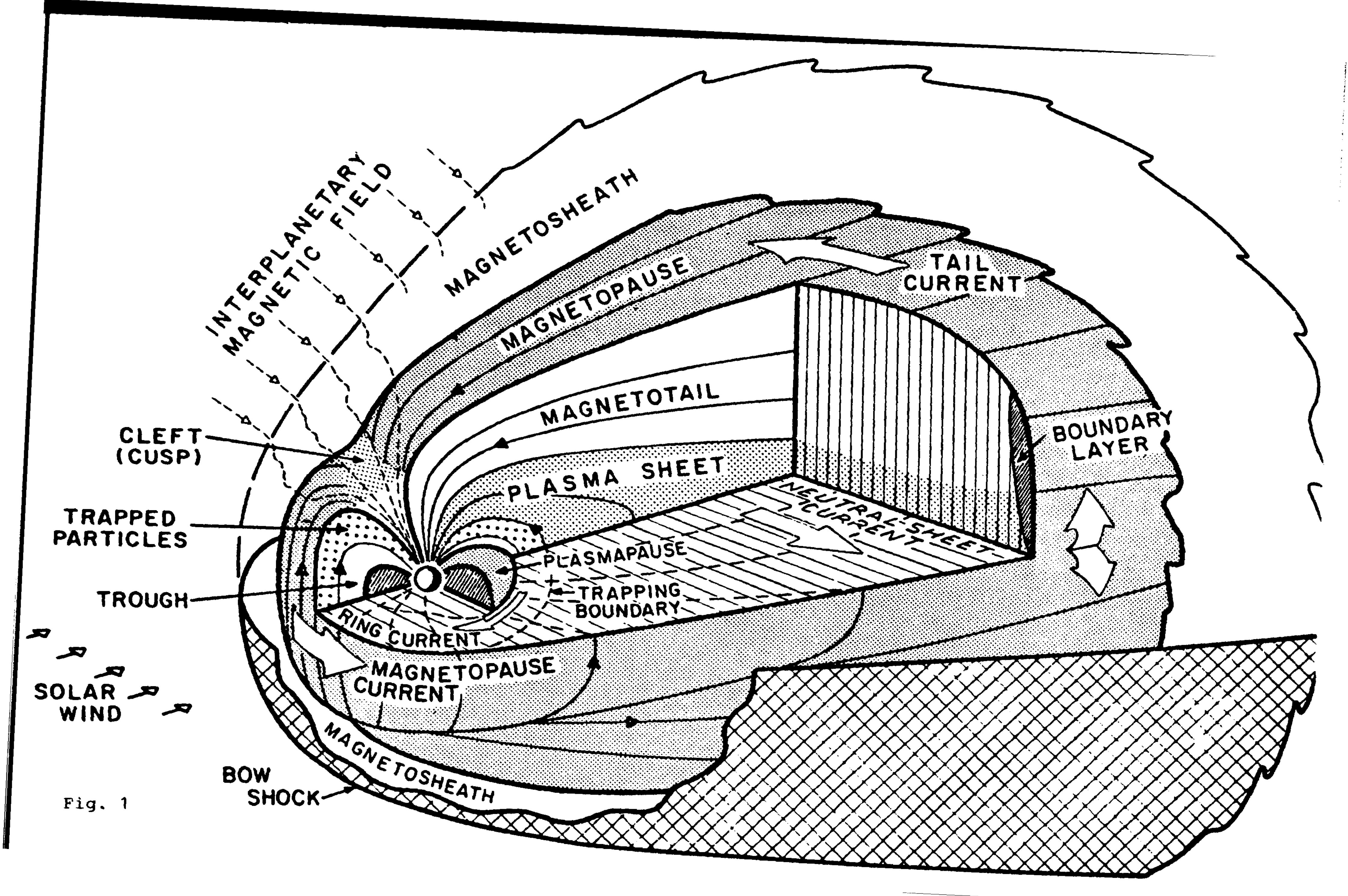
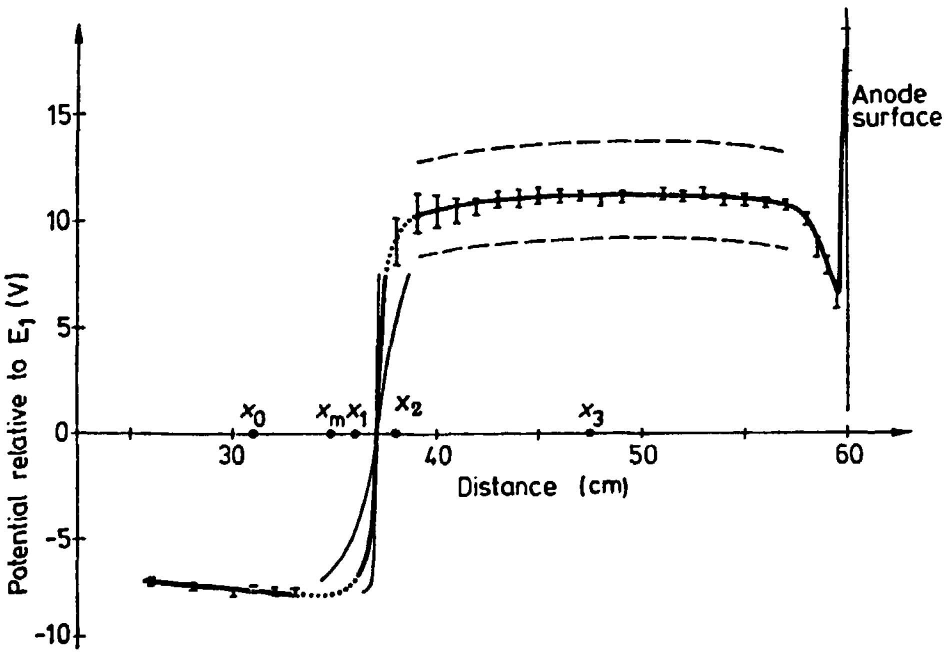

INTERPLANETARY MAGNETIC FIELD
MAGNETOSHEATH
MAGNETOPAUSE
TAIL CURRENT
MAGNETOTAIL
CLEFT (CUSP)
BOUNDARY LAYER
PLASMA SHEET
NEUTRAL SHEET CURRENT
TRAPPED PARTICLES
PLASMAPAUSE
TROUGH
TRAPPING BOUNDARY
RING CURRENT
MAGNETOPAUSE CURRENT
SOLAR WIND
MAGNETOSHEATH
BOW SHOCK

Fig. 1



Anode surface
15
10
5
0
-5
-10
Potential relative to E_1 (V)
x_0
x_m
x_1
x_2
x_3
30
40
50
60
Distance (cm)

Fig. 2

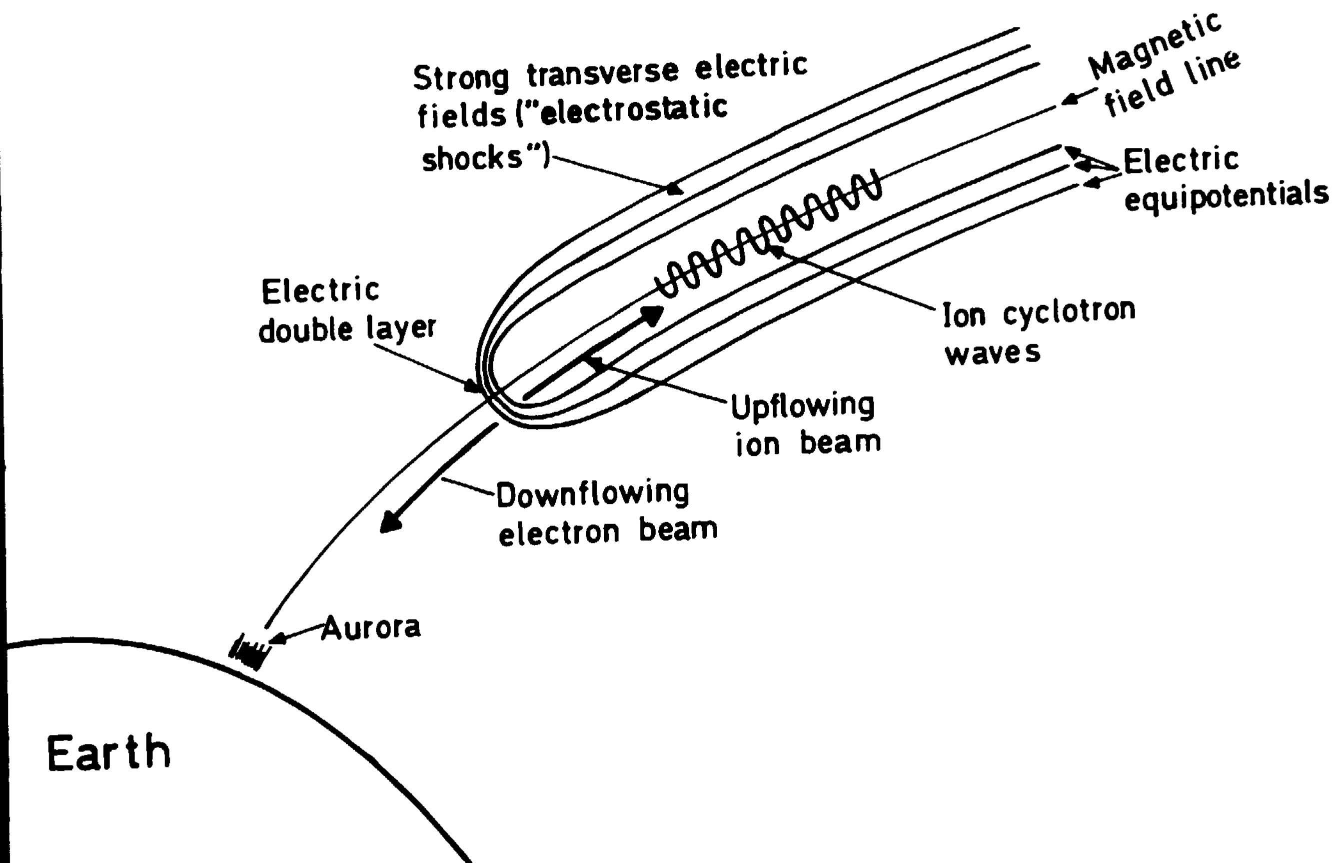

Strong transverse electric fields ("electrostatic shocks")
Magnetic field line
Electric equipotentials
Electric double layer
Ion cyclotron waves
Upflowing ion beam
Downflowing electron beam
Aurora
Earth

Fig. 3

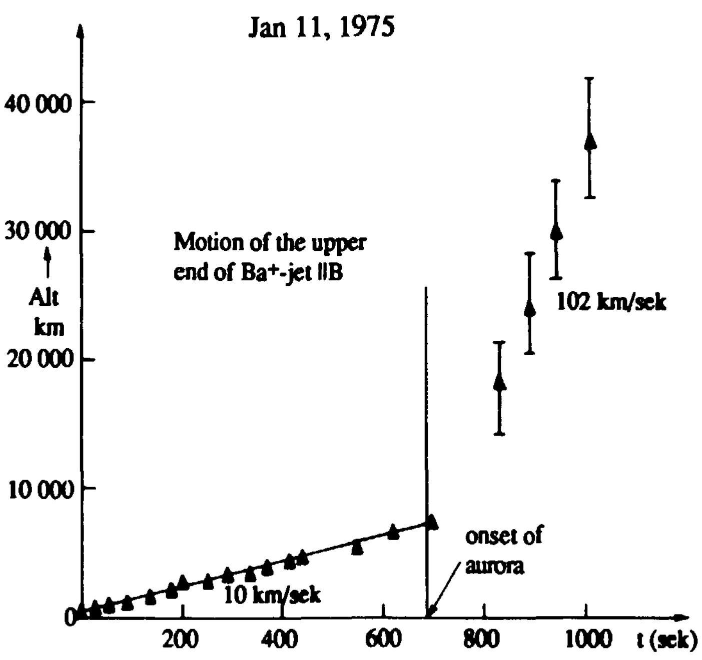

Jan 11, 1975
40 000
30 000
Alt
km
20 000
10 000
0
Motion of the upper
end of Ba+-jet IIB
102 km/sek
onset of
aurora
10 km/sek
200
400
600
800
1000
t (sek)

Fig. 4

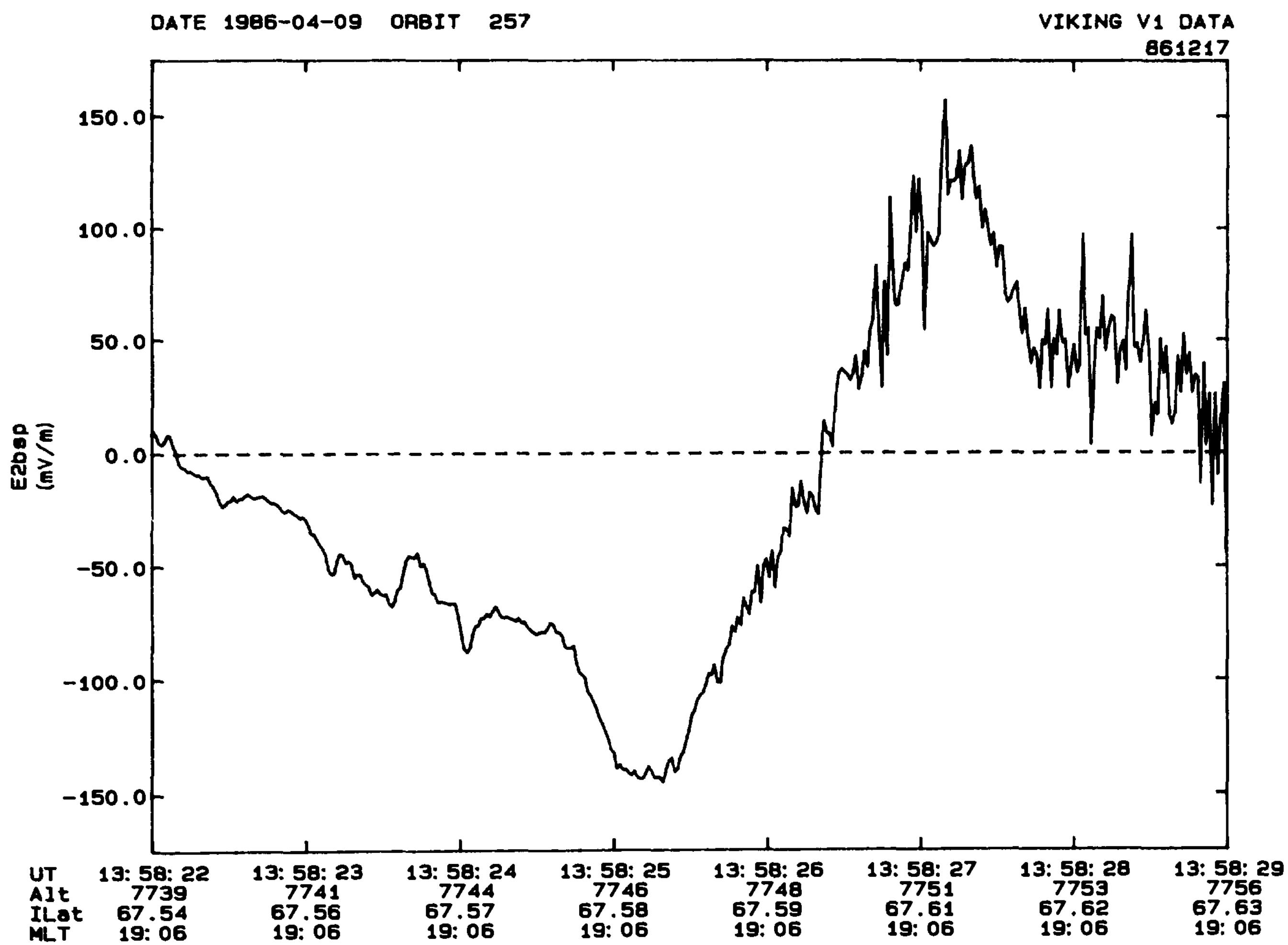

DATE 1986-04-09 ORBIT 257
VIKING V1 DATA
861217
E2bsp
(mV/m)
150.0
100.0
50.0
0.0
-50.0
-100.0
-150.0
UT
Alt
ILat
MLT
13: 58: 22
7739
67.54
19: 06
13: 58: 23
7741
67.56
19: 06
13: 58: 24
7744
67.57
19: 06
13: 58: 25
7746
67.58
19: 06
13: 58: 26
7748
67.59
19: 06
13: 58: 27
7751
67.61
19: 06
13: 58: 28
7753
67.62
19: 06
13: 58: 29
7756
67.63
19: 06

Fig. 5

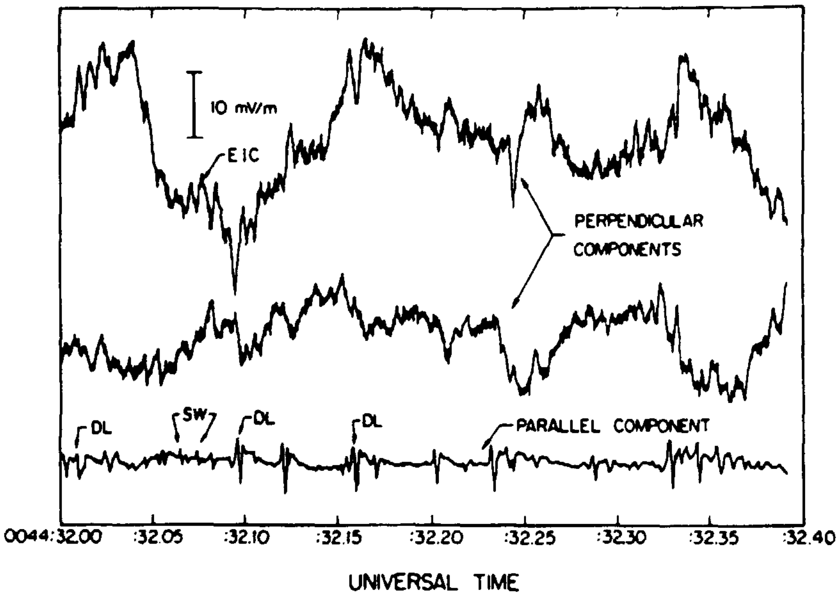
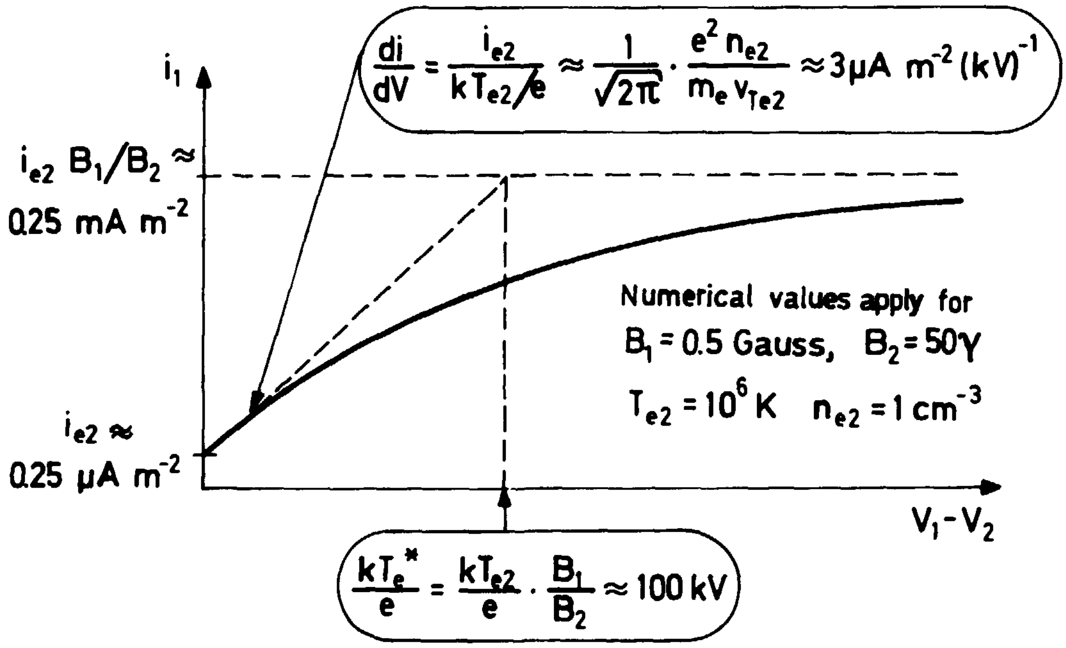
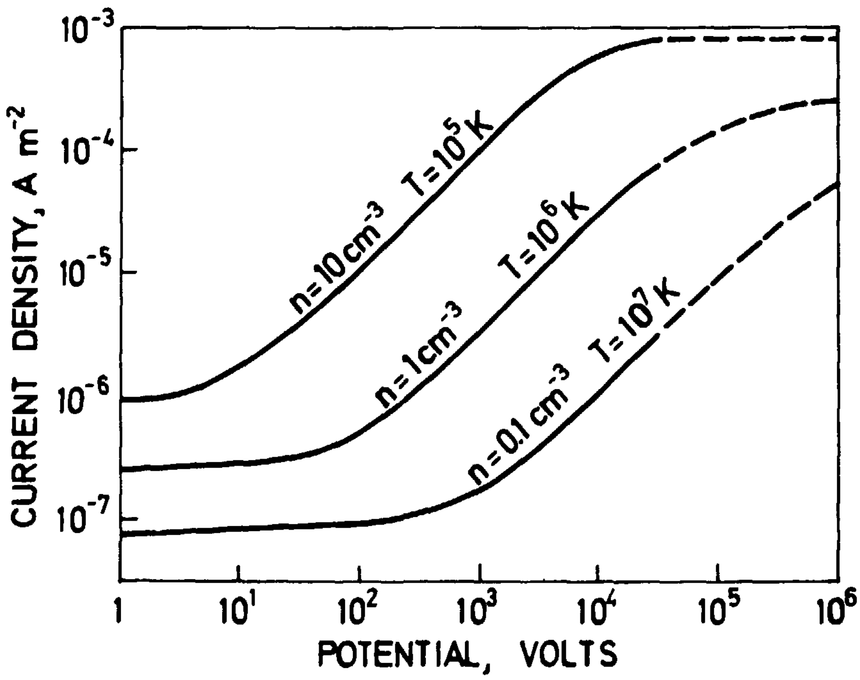

10 mV/m
EIC
PERPENDICULAR COMPONENTS
DL
SW
DL
DL
PARALLEL COMPONENT
0044:32.00
:32.05
:32.10
:32.15
:32.20
:32.25
:32.30
:32.35
:32.40
UNIVERSAL TIME

Fig. 6

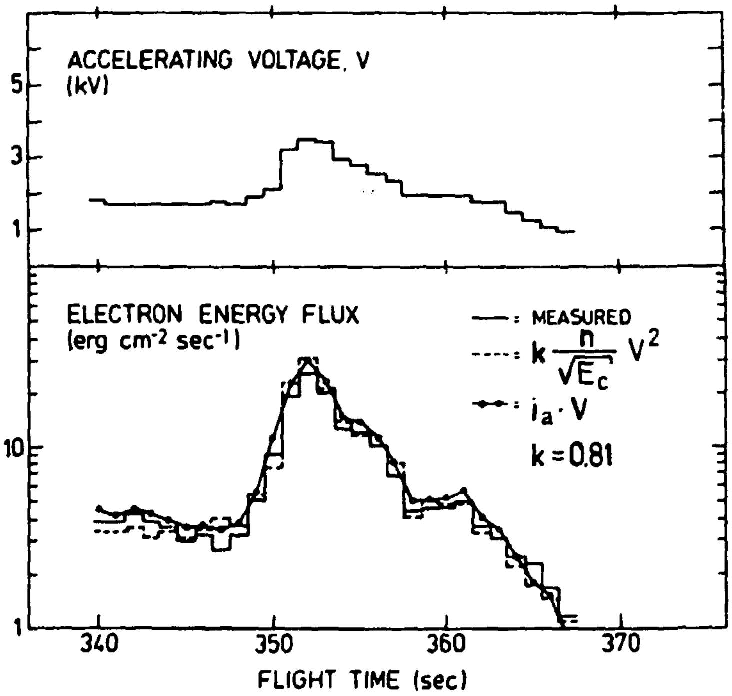


$\frac{di}{dV} = \frac{i_{e2}}{kT_{e2}/e} \approx \frac{1}{\sqrt{2\pi}} \cdot \frac{e^2 n_{e2}}{m_e v_{Te2}} \approx 3\mu A\ m^{-2}\ (kV)^{-1}$
i_1
$i_{e2}\, B_1/B_2 \approx$
0.25 mA m^{-2}
Numerical values apply for
B_1 = 0.5 Gauss, B_2 = 50γ
$T_{e2} = 10^6$ K $n_{e2} = 1\ cm^{-3}$
$i_{e2} \approx$
0.25 μA m^{-2}
$V_1 - V_2$
$\frac{kT_e^*}{e} = \frac{kT_{e2}}{e} \cdot \frac{B_1}{B_2} \approx 100$ kV



CURRENT DENSITY, A m^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$n=10cm^{-3}$ $T=10^5K$
$n=1cm^{-3}$ $T=10^6K$
$n=0.1\ cm^{-3}$ $T=10^7K$
1
10^1
10^2
10^3
10^4
10^5
10^6
POTENTIAL, VOLTS

Fig. 7



ACCELERATING VOLTAGE, V
(kV)
5
3
1
ELECTRON ENERGY FLUX
(erg cm-2 sec-1)
: MEASURED
: k n/√Ec V2
: ia · V
k = 0.81
10
1
340
350
360
370
FLIGHT TIME (sec)

Fig. 8

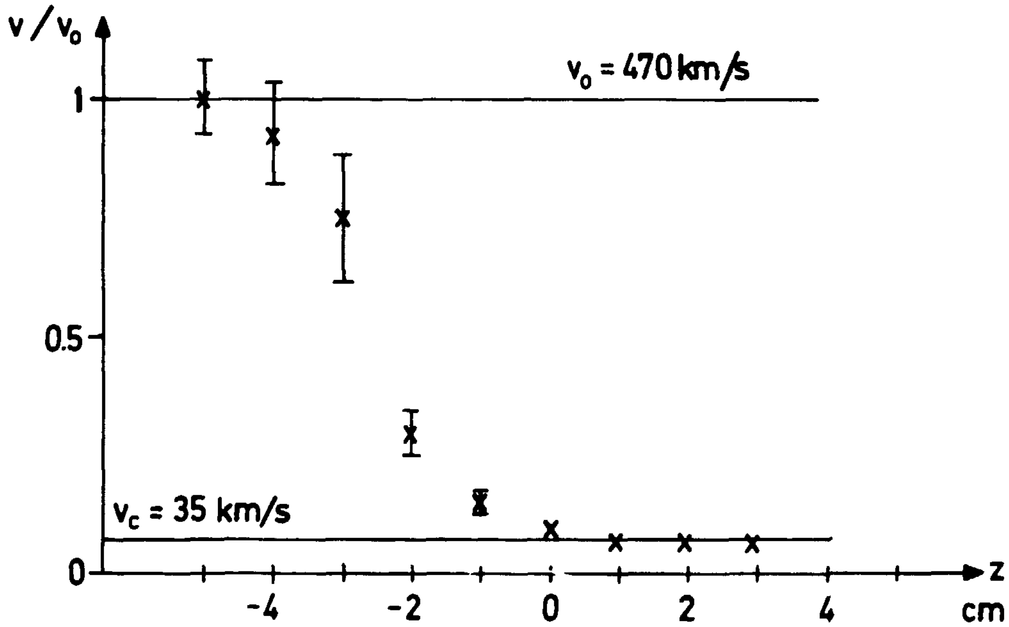


Fig. 9

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THE PLASMA UNIVERSE

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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, and filamentary and cellular structures.

Keywords: Acceleration, Cellular structure, Critical velocity, Electric currents, Electric fields, Filamentary structure, Plasma