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## Plasma in laboratory and space

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**Résumé.** — On étudie les phénomènes du plasma en laboratoire, dans les magnétosphères, et dans les régions astrophysiques les plus lointaines. Il est probable que les qualités de base des plasmas sont partout les mêmes, mais la translation des connaissances entre les régions exige des lois d'échelle d'un facteur allant jusqu'à  $10^{27}$  (= la proportion entre la distance Hubble  $10^{28}$  cm et les dimensions du laboratoire, disons 10 cm).

Les phénomènes du plasma sont compliqués et on ne peut les comprendre qu'au moyen de diagnostics sophistiqués. Jusqu'à présent, les diagnostics en laboratoire ont été développés avec succès et la physique du plasma dans l'espace doit se baser sur un flux de connaissances du laboratoire. Cependant, les mesures *in situ* dans les magnétosphères (y compris l'héliosphère = la magnétosphère solaire) ont atteint un tel niveau de sophistication qu'en quelque sorte, la physique du plasma magnétosphérique devance la physique du plasma en laboratoire.

Ainsi l'exploration des régions astrophysiques (définies comme les régions non encore accessibles aux mesures *in situ*) doit se baser sur une translation des connaissances non seulement à partir de la physique de laboratoire, mais aussi à partir de la physique de la magnétosphère. De plus, une translation des connaissances des magnétosphères au laboratoire peut rajeunir les recherches de la fusion. Les recherches magnétosphériques ont démontré qu'il y a des régions du plasma de deux sortes :

— *les régions du plasma passives*, lesquelles peuvent être décrites par la théorie classique de l'hydrodynamique. Elles transmettent des ondes et des particules chargées de haute énergie, mais si les courants de champ-aligné dépassent une certaine valeur elles sont transférées dans :

— *les régions du plasma actives*. Celles-ci transportent les courants de champ-aligné qui leur donnent une structure de filament ou de feuille d'une épaisseur allant jusqu'à quelques rayons cyclotroniques (ioniques ou électroniques). Elles transmettent l'énergie d'une région à une autre, et produisent des doubles couches électriques qui accélèrent les particules à hautes énergies. On ne peut pas décrire les régions actives par les théories hydromagnétiques. Des conditions limites sont essentielles, et peuvent être introduites par une théorie des circuits. Un traitement équivoque des conditions limites est souvent inévitable dans les théories de fusion magnétique.

La translation des connaissances à partir du laboratoire et des magnétosphères engendre désormais une révolution dans l'astrophysique. Par exemple, la théorie de la formation du système solaire peut se baser sur l'extrapolation de ce que l'on sait de la physique magnétosphérique et de la physique du plasma en laboratoire. Cependant, il y a deux sortes de plasmas qui sont importants en astrophysique et qu'on ne peut pas encore étudier ni en laboratoire ni dans les magnétosphères : les plasmas poudreux, d'importance dans les nuages interstellaires, et les ambiplasmas (se composant de la matière aussi bien que de l'antimatière), d'importance dans le débat cosmologique.

**Abstract.** — Plasma phenomena are studied in the *laboratory*, in the *magnetospheres*, and in more distant *astrophysical regions*. The basic properties of plasmas are likely to be the same everywhere but the transfer of knowledge between the regions requires laws of scaling by a factor of up to  $10^{27}$  (= ratio between Hubble distance  $10^{28}$  cm and laboratory dimensions, say 10 cm).

Plasma phenomena are complicated and can be understood only with the help of a very sophisticated diagnostics. Up to recently, diagnostics in the laboratory was best developed and space plasma physics must be based on a flow of knowledge from the laboratory. However, *in situ* measurements in the magnetospheres (including the heliosphere = the solar magnetosphere) has now reached such a sophistication that in some respects magnetospheric plasma physics is ahead of laboratory plasma physics.

Hence the exploration of astrophysical regions (defined as those regions not yet accessible to *in situ* measurements) must be based on a transfer of knowledge not only from laboratory physics but also from magnetospheric physics. Further, a transfer of knowledge from the magnetospheres to the laboratory may rejuvenate fusion research.

Magnetospheric research has demonstrated that there are plasma regions of two different kinds :

— *passive plasma regions*, which can be described by classical hydrodynamic theory. They transmit waves and high energy charged particles but if the field-aligned currents exceed a certain value they are transferred into.

— *active plasma regions*. These carry field-aligned currents which give them a *filamentary or sheet structure* with thickness down to a few cyclotron radii (ionic or even electronic). They *transmit* energy from one region to another and produce *electric double layers* which accelerate particles to high energies. Active regions cannot be described by hydromagnetic theories. *Boundary conditions* are essential and may be introduced by *circuit theory*. (Erroneous treatment of boundary conditions is often fatal in magnetic merging theories.)

Transfer of knowledge from the laboratory and the magnetospheres is now starting a revolution in astrophysics. For example the theory of formation of the solar system can be based on extrapolation of what is known from magnetospheric and laboratory plasma physics. However, there are two kinds of astrophysically important plasmas which cannot yet be studied in the laboratory or in the magnetospheres : *dusty plasmas*, of importance in interstellar clouds, and *ambiplasmas* (consisting of both matter and antimatter), of importance in the cosmological discussion.

**Introduction : The importance of translation.** — Translation is difficult. You realize this when you attend a meeting in English in a French-speaking country, especially if your mother tongue is neither English nor French. To use another great language for a moment, the Italians say : traduttore-traditore (a translator is a traitor). Also, the types of translation we shall discuss in this paper are not always exact. In modern plasma physics translation is very important in several respects. Plasmas are studied

both in the laboratory and in space, and there are good reasons to believe that in several important respects the basic properties of laboratory plasmas and space plasmas are the same. But as the linear scale of laboratory experiments is — say — 10 cm, a scaling by a factor of  $10^9$  to  $10^{12}$  is necessary in order to apply the laboratory results to planetary magnetospheres or to the solar magnetosphere (heliosphere or interplanetary space). Furthermore to apply the results to galactic and intergalactic — including cosmological — problems we have to

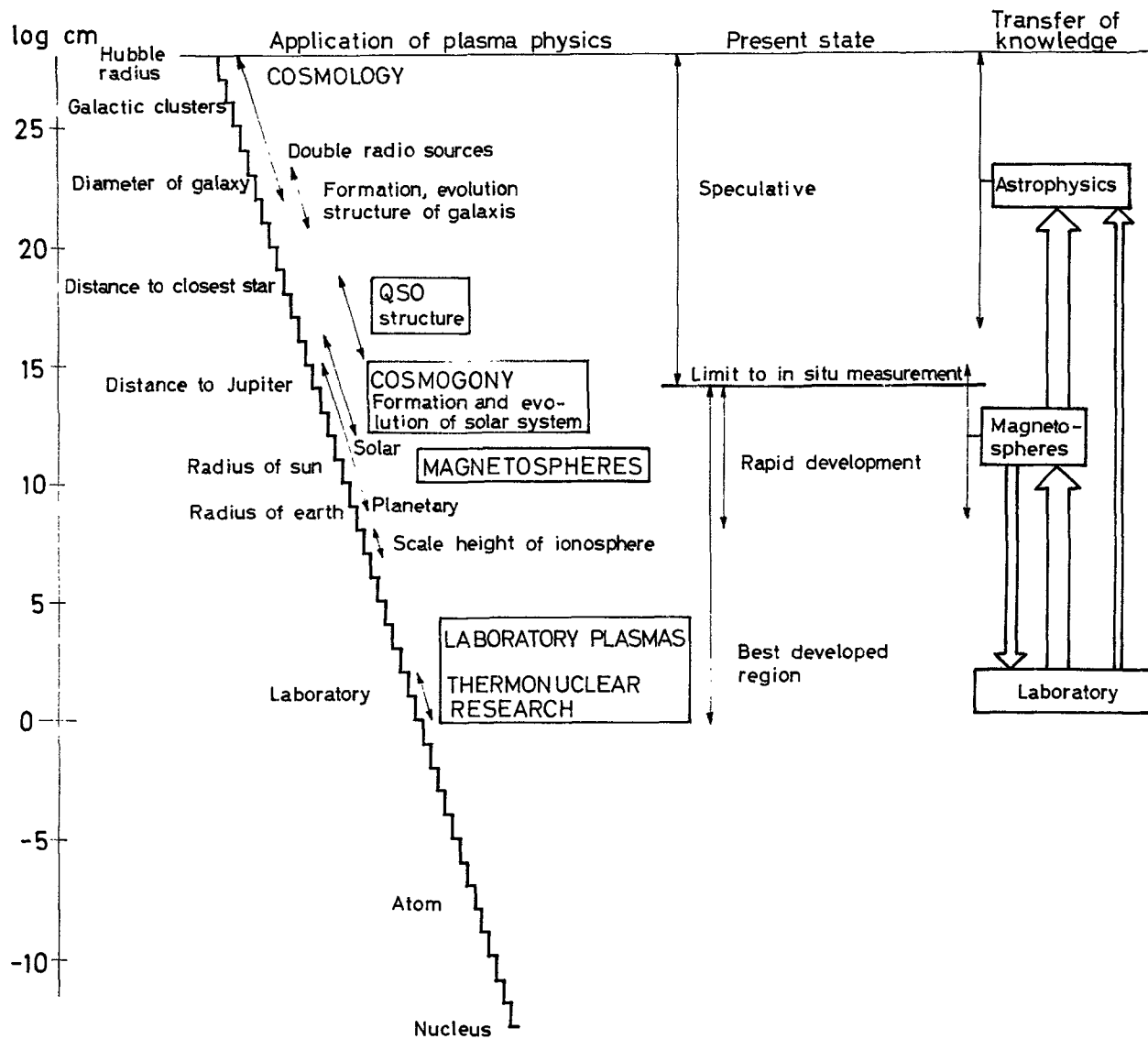


Fig. 1. — Plasmas in laboratory and in cosmos.

scale up by another factor of  $10^9$  to  $10^{12}$  or more. As different plasma parameters obey different scaling laws, translation from one region to another is often difficult.

Figure 1 gives a survey of some important plasma phenomena. Probably several of them are closely related although a scaling by a very large factor is essential in order to realize this. Hence important progress in plasma physics can be expected if we succeed in unifying the different fields. However, this can only be done if we study the very difficult field of scaling plasma phenomena. Hence we shall devote § 2.1 to scaling laws.

There is another translation which also is very important : the translation between a *magnetic field description* and a *current description* of plasma phenomena. Space measurements of magnetic fields are relatively easy, whereas direct measurements of electric currents are very difficult, in many cases impossible. Hence it is natural to present the results of space exploration (by spacecrafts and by astrophysical observations) by pictures of the magnetic field configuration. Furthermore, in magnetohydrodynamic theories, it is convenient to eliminate the current ( $\mathbf{i}$  = current density) and represent electric currents by  $\text{curl } \mathbf{B}$ . This method is acceptable in the treatment of a number of phenomena (see Fig. 2).

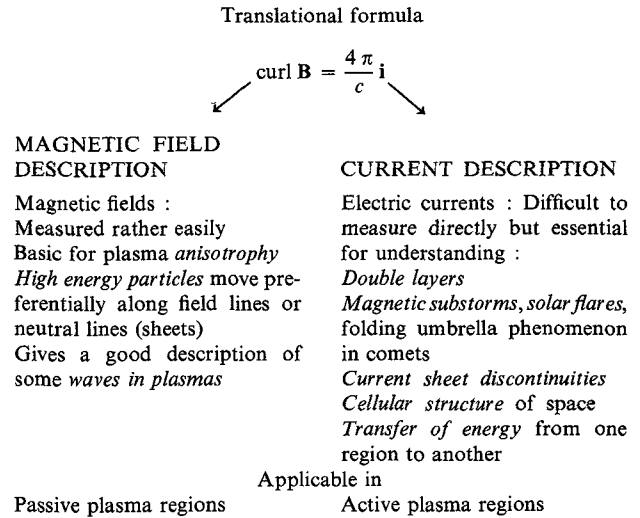
However there are also a number of phenomena which cannot be treated in this way but require an approach in which the electric current is taken account of explicitly (see Fig. 2). The translation between the magnetic field description and the electric current description is made by the help of Maxwell's first equation

$$\text{curl } \mathbf{B} = \frac{4 \pi}{c} \mathbf{i} + \frac{1}{c} \frac{\partial \mathbf{D}}{\partial t} \quad (1)$$

where the displacement current usually can be neglected.

As is shown in figure 2 some kinds of plasma phenomena should be described by the field picture and others by the current picture. Attempts to describe a certain group of phenomena with the wrong formalism often lead to erroneous results (see Alfvén, 1977a). We shall discuss this further in Part II.

**1. Part I. Passive and active plasmas. — 1.1 EXPERIMENTAL AND THEORETICAL APPROACH TO PLASMA PHYSICS. —** Plasma physics has started along two parallel lines. One is the hundred years old investigations in what was called *electrical discharges in gases*. To a high degree this approach was experimental and phenomenological, and only very slowly it reached some degree of theoretical sophistication. Most theoretical physicists looked down on this field, which was complicated and awkward. The plasma exhibited striations and double-layers, the electron distribution was sometimes very far from



The plasma dualism is somewhat analogous to the general particle-field dualism in physics.

The current description requires a new formalism with ELECTRIC CIRCUITS as an important ingredient. This is somewhat analogous to the necessity of introducing a new formalism when the importance of quantum phenomena was discovered.

Fig. 2. — Dualism in plasma physics.

Maxwellian, there were all sorts of oscillations and instabilities. In short, it was a field which was not at all suited for mathematically elegant theories.

The other approach came from the highly developed kinetic theory of ordinary gases. It was thought that with a limited amount of work this field could be extended to include also ionized gases. The theories were mathematically elegant and claimed to derive all the properties of a plasma from first principles. In reality this was not true. Because of the complexity of the problem a number of approximations were necessary which were not always appropriate. The theories had very little contact with experimental plasma physics, and all the awkward and complicated phenomena which had been observed in the study of discharges in gases were simply neglected.

In cosmical plasma physics the experimental approach was initiated by Birkeland, who was the first one to try to connect laboratory plasma physics and cosmic plasma physics. (Neither of the terms was used at that time !) Birkeland observed aurorae and magnetic storms in nature, and tried to understand them through his famous terrella experiment. He found that when his terrella was immersed in a plasma, luminous rings around the poles were produced (under certain conditions). Birkeland identified these rings with the auroral zones. As we know today, this was essentially correct. Further he constructed a model of the polar magnetic storms, supposing that the auroral electrojet was closed through vertical currents (along the magnetic field lines). This idea also is essentially correct. Hence although Birkeland

could not know very much about the complicated structure of the magnetosphere, research today follows essentially Birkeland's lines, of course supplemented by space measurements.

Unfortunately, the progress along these lines was disrupted. Theories about plasmas — at that time called ionized gases — were developed without any contact with the laboratory plasma work. In spite of this — or perhaps because of this — the belief in them was so strong that they were applied directly to space. One of the results was the Chapman-Ferraro theory, which soon got generally accepted to such an extent that Birkeland's approach was almost completely forgotten. For thirty or forty years it was often not even mentioned in text books and surveys, and all attempts to revive it and develop it were neglected.

1.1.1 *Confrontation between theory and experiments.* — The crushing victory of the theoretical approach over the experimental approach lasted as long as a confrontation with reality could be avoided. However, from the theoretical approach, it was concluded that plasmas could easily be confined in magnetic fields and heated to such temperatures as to make thermonuclear release of energy possible. When attempts were made to construct thermonuclear reactors, a confrontation between the theories and reality was unavoidable. The result was catastrophic. Although the theories were generally accepted the plasma itself refused to believe in them. Instead the plasma showed a large number of important effects, which were not included in the theory. It was slowly realized that one had to build up new theories but this time in close contact with experiments.

The thermonuclear crisis did not affect cosmic plasma physics very much. The development of the theories went on because they largely dealt with phenomena in regions of space where no real check was possible. The fact that the basis of several of the theories had been proved to be false in the laboratory had very little effect : one said that this did not necessarily prove that they must be false also in cosmos !

The second confrontation, however, came when space missions made the magnetosphere and interplanetary space accessible to physical instruments. The first results were interpreted in terms of the generally accepted theories, or new theories were built up on the same basis. However, when the observational technique became more advanced, it became obvious that these theories were not applicable. The plasma in space is just as complicated as laboratory plasmas.

A survey of what is known about the magnetospheric plasmas is given for example in a recent report from the Alpbach Symposium on *Magnetospheric Boundary Phenomena* (Battrick, 1979).

1.2 PRESENT STATE OF THE CLASSICAL THEORY. — The classical theory, the foundation of which is due to Chapman and Cowling, has been very successful in accounting for all those phenomena which according to figure 2 are related to the field description. The propagation of waves in plasmas belongs to this category, and so does the motion of high energy charged particles and the drift of low energy particles, including mirror effects. However, a real plasma has many properties which are not easy to describe by the classical formalism. Certainly it is possible to produce externally heated plasmas (e.g. cesium-plasmas) which are completely quiescent, and in these the classical formalism seems to give a good description. For references see for example Motley 1975.

However, as soon as an *electric current* is passed through the quiescent plasma a number of complicated phenomena are produced which require an extensive development of classical theory, sometimes even a new approach (Clark and Hamberger, 1979).

The most important of these *anomalous* properties are :

a) Sometimes the plasma becomes more *noisy* than expected theoretically, sometimes less.

b) The *energy distribution* becomes strongly *non-Maxwellian*; there is a considerable — sometimes very large — excess of high energy particles. The velocity distribution is very often highly anisotropic.

c) The *electron temperature* may be orders of magnitude larger than the *ion temperature* which may be considerably higher than the *neutral gas temperature*, which again may differ from the *wall temperature* or the temperature of the dust (in case the plasma is *dusty*).

1.2.1 *Instabilities.* — There are a very large number of phenomena which often are referred to as *instabilities*. Examples of such phenomena are :

d) At sufficiently *large current density* the plasma may contract into *filaments* (Marklund, 1978).

e) In case the plasma consists of a gas mixture, plasma phenomena often *separate* its components (Marklund, 1979).

f) When the electron drift velocity exceeds the thermal velocity, *double layers* may be produced (Torvén, 1978). Under certain conditions these may explode and produce violent current surges and lead to the acceleration of plasma particles, sometimes up to extremely high energies, even cosmic ray energies (Carlqvist, 1969, 1972, 1973).

g) It is also possible that at current densities above a certain limit the resistivity of the plasma increases by orders of magnitude (*anomalous resistivity*) but arguments for the occurrence of such a phenomenon are still not convincing. (In several cases the forma-

tion of double layers may have been interpreted as anomalous resistivity.)

*h)* When  $\beta$  (= the ratio between gas pressure and magnetostatic pressure) approaches unity, the geometrical confinement of a plasma may be deformed. The long list of such instabilities include the *kink instability*, and *sausage instability*.

**1.3 BOUNDARY CONDITIONS. CIRCUIT DEPENDENCE.** — When applying the classical theory and its modern development, it is often not observed how important the boundary conditions are. Infinite plasma models or models with static boundary condition are often applied to problems with variable boundary conditions. This often gives completely erroneous results : In many theories it is taken for granted that the behaviour of a plasma depends *only* on the local parameters (e.g. density, temperature, magnetic field). This is often seriously misleading. As an example, in a non-curlfree (= current carrying) plasma the properties of the plasma are not only a function of the local parameters but also of the outer *circuit*, in which the current  $I$  closes. For references see Alfvén 1977a, Torvén 1978. Figure 3 shows how is a simple circuit, consisting of an electromotive force  $V$ , a resistor  $R$  and an inductance  $L$ . By changing  $R$  or/and  $L$  the behaviour of the plasma may be changed in a drastic way. The value of  $R$  decides whether the plasma is relatively stable or oscillating. If the plasma contains a double layer, which explodes, the circuit energy  $\frac{1}{2}LI^2$  is released in this. Hence the violence of the plasma explosion is determined largely by the circuit.

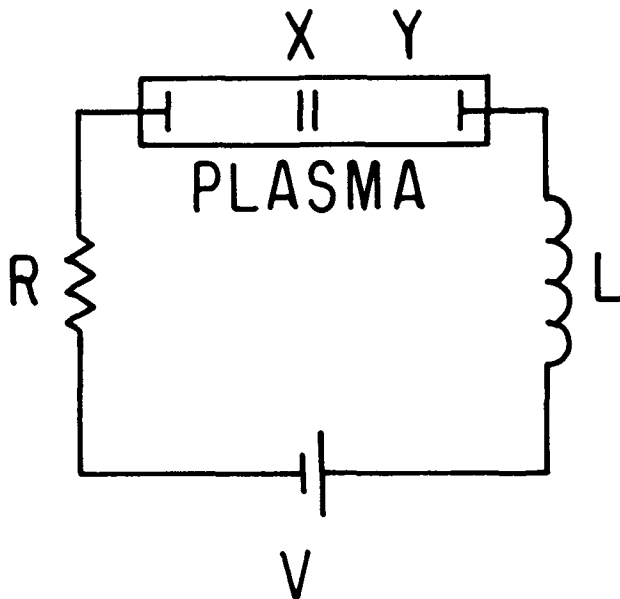


Fig. 3. — If a current flows in a plasma, the plasma phenomena depend partially on the outer circuit. If the resistance  $R$  is smaller than the negative resistance of the double layer  $X$ , the current becomes unstable.

The influence of the *circuit* is essential not only in a laboratory experiment but also in space. In this case the total volume in which the current flows affects the behaviour of the plasma in every point. In many cases it is convenient to introduce the boundary conditions by drawing an *equivalent circuit* (see 1.6).

**1.4 TRANSLATION FROM MAGNETIC FIELDS INTO ELECTRIC CURRENT DESCRIPTION.** — Hydromagnetic phenomena can be described either by using a magnetic field or an electric current picture. The translation is given by eq. (1).

Especially in plasma astrophysics the magnetic field description has been used almost exclusively and the current has not been given explicitly. This is dangerous because there are a number of current-dependent phenomena which cannot be accounted for and in several cases it leads to serious mistakes (see Alfvén, 1977a). Phenomena which cannot be understood without explicitly accounting for the current are :

- A) Energy transfer from one region to another.
- B) Formation of double layers (already mentioned under *f*)).
- C) The occurrence of explosive events such as solar flares, magnetic substorms, *folding umbrella* phenomenon in comets, and stellar flares.
- D) Double layer violation of the Ferraro corotation. Establishing *partial corotation* is essential for the understanding of some features of the solar system (Alfvén and Arrhenius, 1976).
- E) Formation of filaments in the aurora, the solar atmosphere and *nebulae* (already mentioned under *d*)) perhaps also in the Cytherean ionosphere (see Russell, Elphic and Slavin, 1979).
- F) Production of hydromagnetic waves (at least one mechanism which may be the most important one).
- G) Formation of current sheets which may give space a *cellular* structure and hence allow the existence of antimatter in the universe (Fälthammar, Akasofu and Alfvén, 1978).

**1.5 DOUBLE LAYERS.** — In a low density plasma localized space charge regions may build up large potential drops over distances of the order of some tens of the Debye length. Such regions have been called *electric double layers* since an electric double layer is the simplest space charge distribution that gives a potential drop in the layer and a vanishing electric field on each side of the layer. In the laboratory double layers have been studied for half a century, but their importance in cosmical plasmas has not been generally recognized until recently.

Recent reviews of the phenomenon include a general survey (Block, 1978) as well as separate

reviews of experiments (Torvén, 1978) and theory (Carlqvist, 1979). Recent experiments (Coakley *et al.*, 1979; Torvén and Andersson, 1979) have also demonstrated the existence of double layers in magnetized laboratory plasmas. Electric field measurements in satellite orbit have shown the existence of double layer structures above the auroral zone (Mozer *et al.*, 1977; Shawhan *et al.*, 1978).

A double layer can be formed in several ways. An important case is that a double layer is produced when the drift velocity of electrons exceed the thermal velocity.

If the plasma contains a double layer, a strong interaction with the external circuit (Fig. 3) can be produced, because the layer voltage can be strongly fluctuating (Torvén, 1978). *Exploding* double layers were first discovered in mercury rectifiers used in d.c. high power transmission circuits. The phenomenon is likely to be basic for the understanding of solar flares, magnetic substorms and related phenomena. Then the layer voltage is mainly given by  $-L dI/dt$ , which may exceed the normal double layer voltage  $V_0$

by several orders of magnitude. The process may continue until  $I$  vanishes, and then the energy  $\frac{1}{2} LI_0^2$  ( $I_0$  is the initial current) has been released in the double layer, mainly in the form of kinetic energy of ions and electrons.

Measurements at a double layer in a magnetized laboratory plasma (Coakley *et al.*, 1979) show that the equipotential surfaces, which are perpendicular to the magnetic field in the layer, curve at the plasma boundary, where they become parallel to the magnetic field. In this way the plasmas on each side of the layer become surrounded by regions with a strong radial electric field, perpendicular to the magnetic field. This radial field is directed inward on the low potential side of the layer and outward on the high potential side. The situation resembles the situation when two cables are connected by a double layer.

1.6 FIELD ALIGNED CURRENTS AS CABLES. — The discovery that the aurora often is produced by highly anisotropic and almost monochromatic electrons is a strong indication of the existence of electrostatic

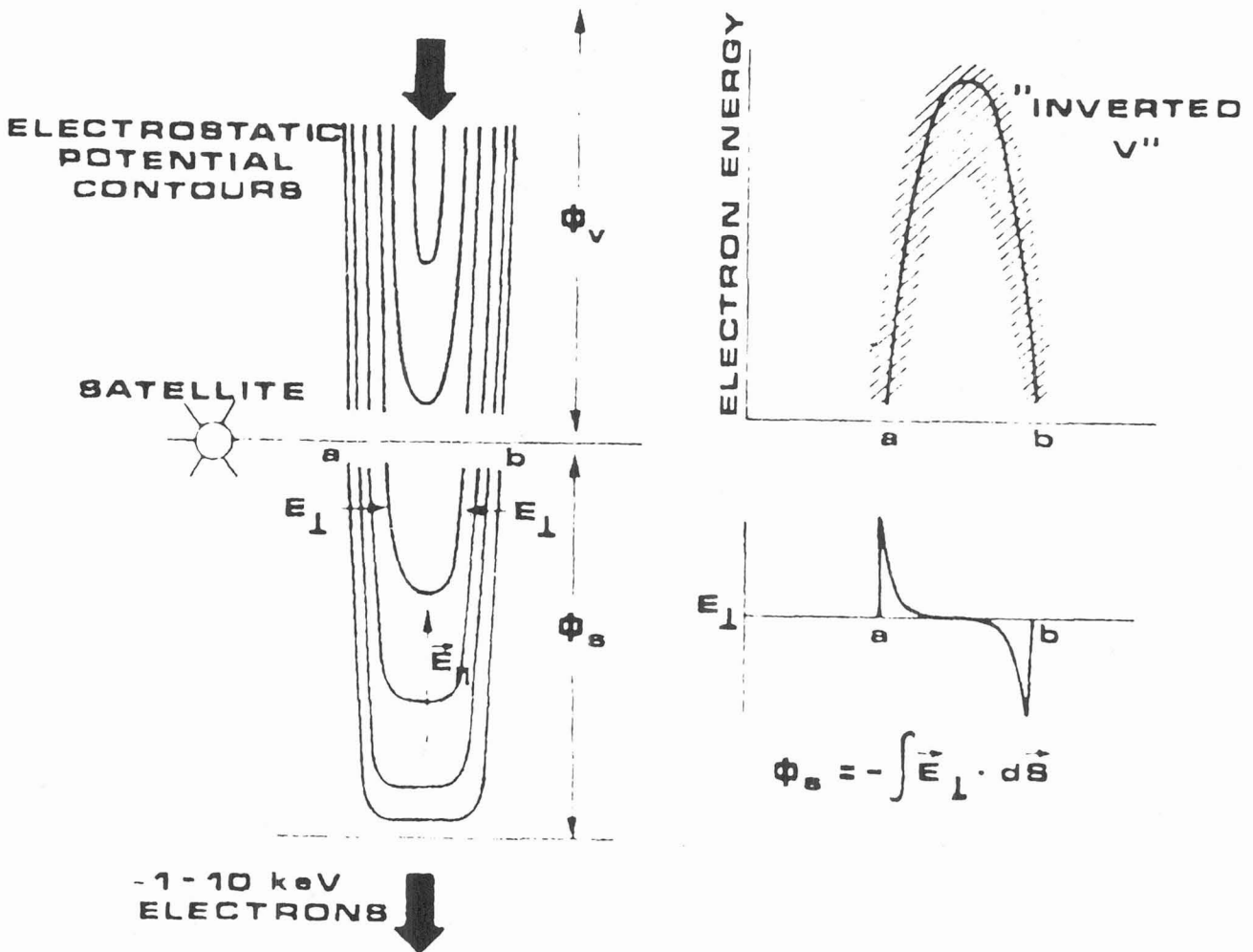


Fig. 4. — (Left) Electrostatic potential distribution according to Gurnett (1972). The magnetic field is vertical. The current-carrying flux tube is insulated from the surrounding plasma by a thin cylindrical shell of rotating plasma, which produces a voltage drop which equals the electrostatic drop in the layer. (Right) Observed inverted  $V$  events confirm the theory.

double layers in the lower magnetosphere. However the electron mirror effect is a competing mechanism for the electron acceleration (Block and Fälthammar, 1976; Fälthammar, 1977, 1978a, 1978b). It is also possible — as suggested by Lennartsson (1977) — that both mechanisms are combined, the mirror effect being the primary cause which gives rise to one or several double layers.

A double layer produces primarily equipotential surfaces perpendicular to the magnetic field. An important problem is how these continue. The inverted  $V$  events and the detection of very strong electric fields perpendicular to  $\mathbf{B}$  indicate a possible solution (see Fig. 4). A filamentary or sheet electric current in the auroral region is *insulated* by such electric fields from the surrounding plasma in which it produces a limited perturbation. There is a similarity with an electric cable in the ocean which carries a strong current in a low resistance metal wire. This is insulated from the conducting water surrounding it by a rubber cylinder, in which the electric field is similar to the radial electric field surrounding the field aligned current in the magnetosphere.

Laboratory plasma experiments have demonstrated a similar phenomenon (Coakley *et al.*, 1979). Often two *cables* are produced, one on each side of a double layer.

If we combine these results with the general tendency of field aligned currents to flow in filaments, we may conclude that *electric currents in plasmas have a tendency to flow in cables*. These are *insulated* from the surrounding plasma by sometimes very strong electric field in the same way as in underwater cables the electric conductor is insulated from the surrounding water. Hence a plasma cable may transfer power over large distances with a limited amount of perturbation of the surrounding plasma.

In the same way as two high power transmission cables connect a generator and a *consumer*, a pair of plasma cables may connect a generator and a *consumer*. The generator often consists of a plasma moving with a velocity component perpendicular to the magnetic field  $\mathbf{B}$  and hence generating an e.m.f.

$$V = \frac{1}{c} \int \mathbf{v} \times \mathbf{B} \, ds$$

where the integral is taken between the ends of the two cables. The consumer may be a double layer accelerating charged particles which later produce light or synchrotron radiation. The consumer may also be a *motor* putting plasma in motion in a distant region. As an example, in the auroral circuit the generator is located in the solar wind and the *consumers* are double layers accelerating high energy particles which later illuminate the night sky in the auroral zone, or a *motor* producing the sun-ward drift in the magnetosphere. (See Fig. 5 and cf. Alfvén, 1979a.)

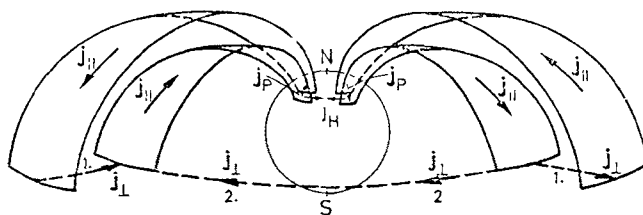


Fig. 5a. — Large-scale Birkeland current sheets shown schematically for a dipolar geometry with alternative closure paths for the lower latitude sheet currents.

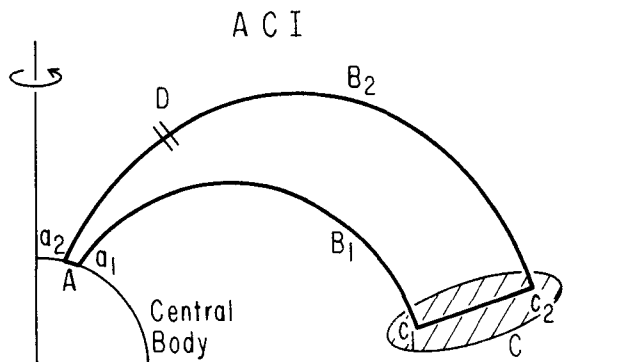


Fig. 5b. — Auroral Circuit I. Currents along the magnetic field lines  $B_1$  and  $B_2$  close through the upper atmosphere at A and through the magnetospheric plasma at C. The e.m.f. is produced by motion at A and C. The current may produce one or more electrostatic double layers D.

The tendency of electric currents to flow in cables makes the circuit approach a reasonable first approximation to many plasma problems.

1.7 DIFFERENT TYPES OF PLASMA REGIONS. — What has been said above might be summarized and elaborated in the following way : it seems that at least in low density cosmic plasmas there are three different types of regions.

1.8 « PASSIVE » PLASMA REGIONS. — These regions may transmit different kinds of plasma waves and flow of high energy particles. There may be transient currents perpendicular to the magnetic field changing the state of motion of the plasma but not necessarily associated with strong electric fields and currents parallel to the magnetic field. A plasma of this kind fills most of space.

If in an initially homogeneous plasma the parameters in one region are changed above a certain limit the plasma often reacts by setting up a discontinuous interphase. Instead of a continuous space variation of the parameters the plasma *prefers* to produce a discontinuity interphase separating two almost homogeneous regions. This may sometimes be the origin of *double layers*, taking up voltage differences, and *current sheets*, separating regions of different magnetization, temperature, and density.



1.9 « ACTIVE » PLASMA REGIONS. — Besides the passive plasma regions there are also small but very important regions where filamentary and sheet currents flow (Alfvén, 1977a). By transferring energy and producing sharp borders between different regions of passive plasmas, they are of decisive importance to the overall behaviour of plasmas in space. There are two different — but somewhat related — types of such regions which we shall call *plasma cables* and *boundary current sheets*.

1.9.1 *Plasma cables*. — Plasma cables seem to be reasonably stable formations which could be considered as entities which are important for the understanding of plasma phenomena. (Of course their interior structure should be described by classical theory.) The plasma cables are either filaments or *flattened filaments*, sheets with not very large extension. They carry an electric current parallel to the magnetic field, and this is the primary cause of their properties. They are often very efficient in transferring electromagnetic power from one region to another. The cables are embedded in passive plasmas, which have essentially the same properties in all directions around them. They are *insulated* from the surrounding by a thin cylindrical electrostatic sheath (or double layer) which reduces the interaction with the surrounding. In the magnetosphere and upper ionosphere the density in the cable is sometimes lower than in the surrounding (Block and Fälthammar, 1968). In other cases the density in the cable may be much larger than in the surrounding, because ionized matter is pumped into the cable from the surrounding (Marklund, 1979). By doing so selectively, the chemical composition in the cable may differ from that of its surrounding. Besides the cylindrical electrostatic sheath there are often longitudinal *double layers*, in which a considerable part of the power which the cable transmits may be converted into high energy particle energy. The double layers sometimes explode, and this produces excessively high energy particles (Carlqvist, 1978). Then the current in the cable may be disrupted and switched into another circuit (Boström, 1974, 1975). Such plasma cables have been discovered (or are likely to exist) in several places :

(a) *The auroral current system* consists of plasma cables, sometimes filaments — possibly associated with auroral rays — and more frequently sheets — possibly associated with auroral arcs. The inverted V events are likely to be produced by cables (Block, 1978). In the auroral zone such cables transfer energy from the equatorial plane to the auroral zone, and double layers are likely to be the direct cause of some types of luminous aurorae.

(b) *Solar prominences*. The electromotive force is due to motions in the photosphere in combination with the photospheric magnetic fields (Fig. 6). The prominences are often filaments but sometimes sheet-

like (quiescent prominences). Double layers are often produced, and when they explode, they cause solar flares. *Spicules* are probably small scale versions of the same phenomenon.

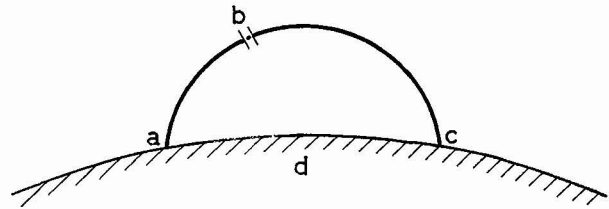


Fig. 6. — Prominence circuit consisting of a magnetic field tube abc and a subphotospheric connection cda. The

$$\text{e.m.f.} = \int_a^c v \times B \cdot ds$$

is produced by motions with velocity  $v$  in the presence of a solar magnetic field  $B$ . It produces a current in the solar corona which collects matter from the surrounding (Marklund, 1978, 1979). If the current density exceeds a certain limit a double layer  $b$  is formed. If it explodes the inductive energy  $\frac{1}{2} LI^2$  in the circuit is very rapidly released at the point of disruption. Note that the prominence circuit is a simplified version of the well-known auroral circuit, which makes it possible to construct it with a high degree of certainty.

(c) *Coronal streamers and polar plumes*. As we expect that the heliospheric large current system should connect with the sun in the polar regions and in the equatorial region, it seems likely that these

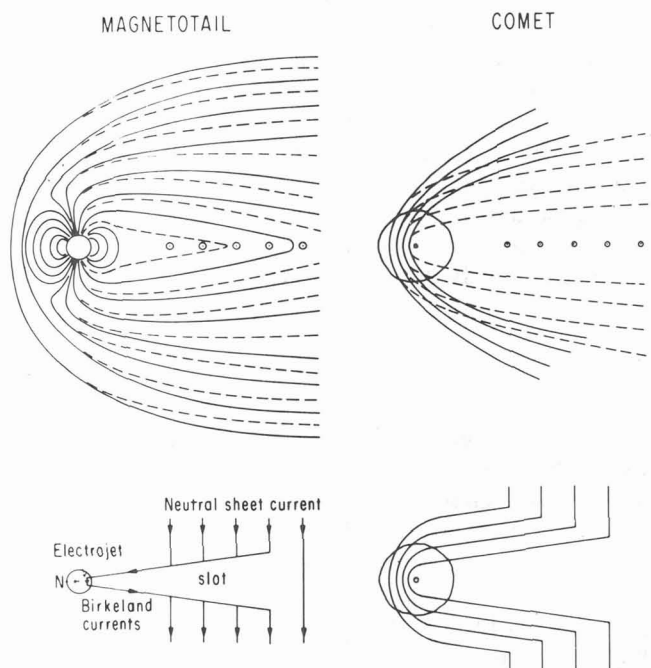


Fig. 7. — Similarity between the magnetosphere and a comet (Ip and Mendis, 1976). Current disruption which causes repetitive substorms in the magnetosphere also causes the *folding umbrella* phenomenon in comets, and simultaneous brightening of the coma.

phenomena are basically similar to the solar prominences. The main difference is that the prominences are produced in a photospheric circuit, whereas the streamers and plumes are caused by the large heliospheric current system.

(d) The filamentary structure in *cometary tails* (Mendis, 1978 ; see Fig. 7), and in *interstellar nebulae* may be caused in the same way. *Stellar flares* are probably due to the same mechanism as solar flares. It has also been suggested that the transfer of energy to the *double radio sources* from the galaxy which normally is located half the way between them is due to a plasma cable of this type (Alfvén, 1978a).

Filaments are more easily seen at large distances whereas sheets are more easily detected from spacecrafts.

1.9.2 *Ionospheric projection of active and passive plasma regions.* — The drastic difference between active and passive plasma regions is visualized by a look at the ionosphere. The auroral zones are those

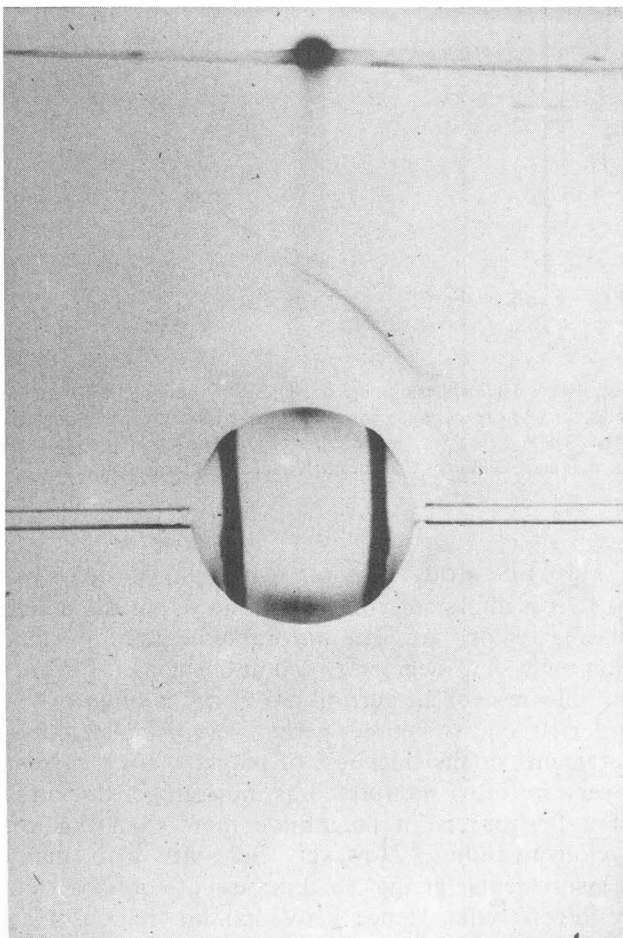


Fig. 8. — The auroral zones. If a terrella is placed in a plasma, the terrella is dark in the regions where the field lines connect with passive plasma regions (polar caps and low latitudes) but luminous in the regions which connect with active plasma regions (auroral ovals). The figure shows a modern version (Block, 1955) of Birkeland's experiment. Space photographs of the night side of the earth are similar (although usually perturbed locally).

regions of the ionosphere which connect magnetically to active regions in the magnetosphere. The rest of the ionosphere connects with passive plasma regions, and hence receives very little energy from above (Fig. 8).

It is tempting to identify the different auroral patterns with the different active structures in the magnetosphere : auroral rays may derive from active filaments, arcs from sheets, draperies from perturbed sheets. However there are quite a few rather complicated phenomena in the transitional region between the magnetosphere and the ionosphere. Further, there are horizontal currents in the upper ionosphere, which also may produce luminous effects. Hence the relation between the structure of the active plasma in the magnetosphere and the visually observed aurora is very complicated.

1.9.3 *Boundary current sheets.* — In striking contrast to the current layer we have discussed above, there is another type of current layers which form boundaries between two regions of plasma which have drastically different parameters. The basic difference is that the cables we have discussed carry such small currents that their magnetic field is small compared to the exterior field, whereas in the boundary current sheets the current is large enough to change the surrounding field very much. In the magnetosphere there are three such layers (see Alfvén, 1979a ; Heikkila, 1975 ; Heikkila and Block, 1977) :

*The magnetopause*, which often is a very thin current layer (a few cyclotron radii thick) and separates two regions with opposite magnetic fields (directed northward and southward), but with other parameters (pressure, density) not necessarily very different (Fig. 9).

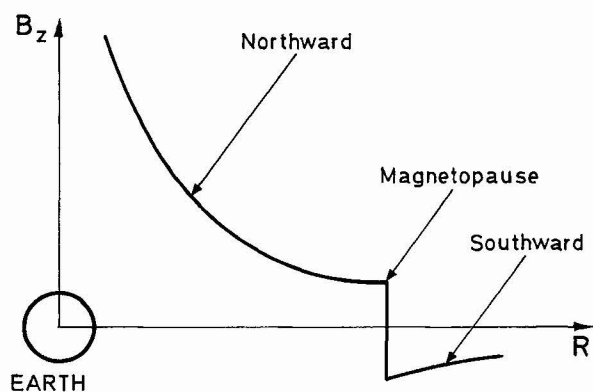


Fig. 9. — Magnetic field reversal in the magnetopause.

In many cases a spacecraft passing the region of the magnetopause observes more than one magnetic discontinuity. This is usually interpreted as an indication that the magnetopause moves very rapidly out and in. The data can probably also be interpreted as a *folding* of the magnetopause current layer. Auroral

draperies are often observed to fold so that they become *S*-shaped. This process may continue, resulting in a triple layer. Similarly the heliospheric boundary layer is known to be wavy. By analogy it is quite reasonable that the magnetospheric current layer is folded so that a spacecraft traverses it three times. A model of this has been given by Smith (1979). The current layer may be very thin (a few cyclotron radii) and need not necessarily move. *The neutral sheet in the tail* also separates two regions with opposite magnetic field (directed towards and away from the Earth). Other parameters are usually similar. It is believed that the magnetic field often has a small northward magnetic field superimposed.

Further there is a *current layer in the front* of the magnetopause which separates a region of very weak magnetic field in the solar wind from a much stronger field (three times or more) between the front current and the magnetopause. This current layer is usually referred to as the *bow shock*. It transforms a large part of the solar wind kinetic energy into electromagnetic energy (Alfvén, 1979).

In the *heliosphere* there is a very extended current layer in the *equatorial plane*, waving up and down, which separates an inward magnetic field from an outward directed field (Fig. 10) (Alfvén, 1977a; Akasofu, Lee and Gray, 1979).

Current layers similar to those in the magnetotail and heliosphere have also been discovered in the *Jovian magnetosphere and in other magnetospheres*, and theoretically inferred in the *tails of comets*.

The magnetotail current sheet is likely to produce explosive double layers (Carlqvist, 1978; Kan *et al.*, 1978) causing magnetic substorms, and the cometary current sheet probably does the same, causing the folding umbrella phenomenon (Mendis, 1978). Whether other current sheets have the same property is not known.

There are a number of theories of each of these current layers but unfortunately a general theory covering all these very important phenomena seems still to be lacking.

The discovery of these layers (the first one, the *plasmopause*, discovered by Cahill) looks to many as the most sensational of all space research discoveries (although Dungey (1961, 1964) had predicted them to some extent). No one had guessed that such current layers had such a remarkable stability. The existence of such layers change our views of the structure of space plasmas (Fälthammar *et al.*, 1978). As of course it is impossible to claim that such layers exist only in those regions where spacecrafts have made *in situ* measurements, we must drastically revise our views of the structure of space. The existence of such boundary layers are likely to lead to the conclusion that space everywhere (interstellar space and intergalactic space) has a *cellular structure*. We shall discuss the consequences of this later, especially in 2.5.1.

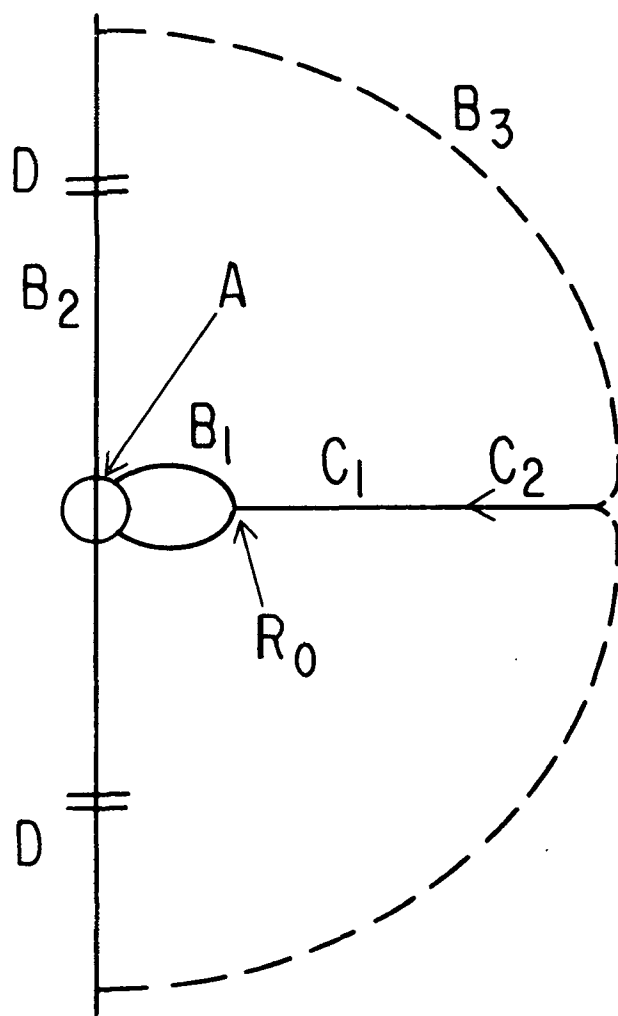


Fig. 10. — Heliospheric Circuit. The Sun acts as a unipolar inductor (A) producing a current which goes outwards along the axis ( $B_2$ ) and inwards in the equatorial plane  $C_2$ ,  $C_1$  and along the magnetic field lines  $B_1$ . The current closes at large distances ( $B_3$ ).

#### 1.10 FINE STRUCTURE OF ACTIVE PLASMA REGIONS.

— It is a matter of controversy how thin the active plasma regions are. The auroral zone has an extension of a few degrees (= some  $10^7$  cm). However the thickness of an auroral arc or ray is often of the order  $10^5$  cm, sometimes perhaps even smaller. Measurements of the thickness of magnetopause current layers are often interpreted as indicating a thickness of a few orders of magnitude more than the ion cyclotron radius. However there are also many measurements giving thicknesses of only a few cyclotron radii. Hence active plasma regions may have a *fine* structure of the order of a few cyclotron radii which are the basic elements which determine the basic properties of active plasmas.

Solar prominences are supposed to be  $10^8$  or  $10^9$  cm in diameter, but in many cases a filamentary fine structure is observed in the prominence, indicating that the prominence should be considered as a *rope*

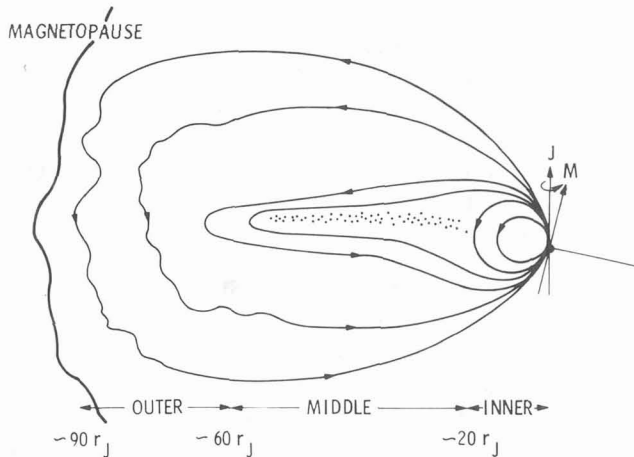


Fig. 11. — Jovian magnetosphere (Smith, 1979).

consisting of a multitude of small wires. It is possible that also the smallest observed filamentary structure in the sun (some  $10^7$  cm) consists of still smaller filaments, perhaps going down to  $10^5$  cm structures like those observed in the ionosphere.

Hence it seems doubtful whether a deeper understanding of the properties of a plasma is possible before we are able to study its fine structure. Hence the study of active plasma regions according to the principles we have discussed may very well be an important step forward but should not be regarded as the final step.

An important discovery of small scale current ropes (diameter  $10^6$  cm) was made recently by the Pioneer Venus Orbiter (Russel, Elphic, Slavin, 1979). The Cytherean ionosphere is penetrated by a large number of twisted magnetic filaments of the same kind as recently studied theoretically by Marklund (1978). They differ from the auroral rays of our ionosphere in the respect that they are magnetically contracted. It is possible that the observed phenomenon is the long sought-for filamentary structure which should be the basic constituent of filamentary currents in prominences, coronal streamers etc., perhaps also in cometary tails, and cosmic plasmas in general.

**1.11 DISCUSSION : DUSTY PLASMA, AMBIPLASMA.** — We have here described three typical regions of plasma : *passive plasmas*, which seem to be the most common type in the magnetospheres of the planets and the sun, *cables* which are found in the auroral zones, and *boundary current sheets*, of which the magnetopause is the best studied example. However it is quite likely that there are many cases which are intermediate between these three types. A detailed analysis is needed before it is possible to decide this.

Another important fact is that cosmic plasmas very often are *dusty*. Interstellar clouds are typical examples. It is likely that the solar system was formed out of

such a cloud, which means that our solar system should be a product of the evolution of a dusty plasma (Alfvén and Carlqvist, 1978). Although the largest part of a dusty cloud consists of a *dusty passive plasma*, the small *dusty active plasma regions* are likely to be of decisive importance for the evolution of the cloud into a solar system.

As the dust particles usually are charged — especially in the active plasma regions — the motion of small dust grains (up to  $10^{-3}$  cm or in certain cases even more) may be dominated by magnetic field, so that they constitute superheavy plasma particles. In the active plasma regions, where there are many high energy electrons, the grains may have high electrostatic potentials (1 000 V or more) so that they are more efficiently trapped.

As it seems possible that the universe is symmetric with respect to matter and antimatter, plasmas consisting of protons, antiprotons, electrons and positrons should also be investigated. The study of the evolution of such an *ambiplasma* is important for the cosmological discussion. See 2.5.1.

**1.12 CHEMICAL DIFFERENTIATION IN A PLASMA. —**

There are a number of plasma processes producing chemical differentiation (Arrhenius, 1976 ; Alfvén and Arrhenius, 1976). One important mechanism is the following. In a partially ionized plasma, the elements with low ionization potentials, which in general are the heavy elements, may be completely ionized, whereas the elements with high ionization potentials, such as H, O, and especially the noble gases, are completely non-ionized. As electromagnetic forces act exclusively on the former group, a chemical separation may be achieved.

Chemical separation in cosmic plasmas have actually been observed (Schoeler *et al.*, 1979). It seems likely that the mentioned process is responsible for the separation, but there seems also to be other separating processes.

Also, the dynamics of the dust in the plasma differs from the gas component, which means that the laws of motion of the chemical substances condensed as grain differs from the non-condensed components.

It has been claimed that a cosmic plasma necessarily must have a uniform chemical composition because of *turbulence*, and for a long time there has been a general belief that *cosmical abundances* of chemical elements could be defined which represent an invariable chemical composition of cosmic matter everywhere. This belief is now decisively contradicted by observations. In part it had originated because of a semantic mistake. When large non-thermal Doppler broadening was observed this was called *turbulence* and it was thought that a chemical mixing must take place. In reality the Doppler broadening can often be attributed to the passage through the plasma of non-mixing waves. As another example — if a spacecraft passes a region with *filamentary*

structure, it will register rapidly varying density and magnetic field, but it is misleading to call the region *turbulent* and conclude that chemical mixing takes place. Instead — as we have seen — in a region with filamentary structure chemical differentiation may take place.

**2 Part II. Scaling and application.** — 2.1 SCALING PROCEDURES. — As it is likely that the basic properties of a plasma are the same in the *laboratory*, the *magnetospheres*, and in more distant *astrophysical regions* a transfer of knowledge between these regions may help us to understand plasma phenomena.

The advance of thermonuclear research has resulted in a better knowledge of plasma phenomena in the laboratory, and much of this knowledge can be transferred to space problems. However thermonuclear investigations are increasingly focussed on those problems which are believed to be of technical interest, and they are not necessarily those which are most interesting in cosmical physics. Hence for the contact between the different fields of plasma physics, it is essential to make *laboratory experiments especially designed for simulation of cosmic problems*. A survey of such experiments has been given by Fälthammar (1974), and by Block (1976). Further it is now possible to make active experiments out in space. As Fälthammar summarizes it, this means that the era of active experiments in the magnetosphere may bring a new importance to space-related laboratory experiments. This is a consequence of the shift of emphasis from exploratory measurements in the early space age to an increasingly sophisticated physics-oriented effort. In such an effort, certain types of laboratory experiments can enhance the fruitfulness of the experiments in space by improving the understanding of basic plasma physical processes of importance in the space environment.

Laboratory experiments for studying space phenomena have traditionally been of a type which we may refer to as *configuration simulation*. i.e., they have aimed at simulating, if only in some limited sense, the actual configuration of a system (e.g., the whole magnetosphere) as well as some of the physical processes taking place within it. The basic difficulty in configuration simulation stems from the large scaling ratio. It puts very severe limits on the possibilities of scaling in a strict sense and necessitates compromises which lead to what may be called qualitative scaling. In spite of these constraints, interesting results have been achieved in a number of cases using model experiments of the terrella type. The magnetic neutral sheet in the nightside magnetosphere is such a system, for which interesting simulation experiments have been performed.

Another type of experiments, which should be considered, may be referred to as *process simulation*. The knowledge gained from direct observations in

space has shown that the real magnetospheric plasma behaves in a considerably more complicated way than the simple models of it that have been extensively used. This necessitated a new approach, where the actual behaviour of real plasmas had to be determined experimentally and accounted for, even where not well understood theoretically. In the case of the magnetosphere, it is more difficult, and in some cases impossible, to make a corresponding consolidation of the experimental basis. Usually, measurements can be made only at a single point at a time, and in an orbit-governed time-space sequence, which is often far from optimum. Even within these limits, the costs of space missions imposes further serious constraints. The advent of active experiments in space is one important step towards a better understanding of the real space plasma. However, the fruitfulness of this activity should be greatly enhanced if combined with suitably designed laboratory experiments. Such experiments need not necessarily simulate the actual configuration of a phenomenon in space, but they should adequately simulate the plasma physical process in question (e.g. collisionless resistivity). We may refer to simulation of this kind as *process simulation*. In many cases this involves simulating only the local behaviour of a plasma, and then the problem of huge scaling factors disappears.

The relevance of laboratory plasma experiments is not limited to simulation. In the past, essential concepts such as Birkeland currents, electric fields along magnetic field lines, electrostatic particle acceleration, and the role of current filamentation and non-homogeneity in general were conceived as a result of close contacts with laboratory plasma experience in general. In the future, too, it can be expected that progress in space plasma physics can benefit from laboratory plasma experiments in a much broader sense than that of simulation (Fälthammar, 1974).

Experiments have been made by Podgorny and Sagdeev (1970), Podgorny (1976) and by Danielsson and Lindberg (1964, 1965).

Theoretical laws for scaling are well-known since long ago (summarized e.g. in Alfvén and Fälthammar, 1963). A recent detailed survey is given by Siscoe (1979). However it should be remembered that scaling laws depend on a theoretical formalism which probably is applicable to passive plasmas, but it has not yet been clarified how a scaling between active plasma regions should be made.

Predictions of what could be expected at the first space mission to a planet have so far not been very successful.

(Traduttore-traditore !) The predictions are of course based on generally accepted theories, and almost every new space mission has demonstrated that our understanding of space plasmas is still not very good.



2.2 CURRENT MODELS. — As pointed out in 1.4 a systematic translation from the usual magnetic field models to electric current models should be made. We shall here discuss a few attempts to such translation, which demonstrate what new aspects can be obtained from current models.

2.2.1 *Auroral circuit.* — Zmuda and Armstrong (1974) made magnetic field observations in the auroral region, and derived the electric current system from these, which was also discussed by Rostoker and Boström (1976). A simplified model is shown in figure 5. The electromotive force is produced by the sunward convection in the equatorial plane. A current flows in the circuit  $C_1 B_1 A_1 A_2 B_2 C_2$  and transfers power to a double layer  $D$ , which accelerates charged particles. The circuit describes the conversion of (1) kinetic energy (of the convection) into (2) electromagnetic energy (of the circuit), further into (3) electrostatic energy (in the double layer) and into (4) kinetic energy of beams of particles, and finally into (5) light and ionisation (in the auroral ionosphere). (See Alfvén, 1977a.)

2.2.2 *Heliospheric circuit.* — The magnetic data from space measurements in the solar wind can be used for construction of the heliographic circuit (Alfvén, 1977a). The result is shown in figure 10. The translation alone leads to the following conclusions :

- (a) There must be essentially radial currents of  $1.5 \times 10^9$  A in each of the polar regions of the sun.
- (b) The currents must close through the sun, which acts as an unipolar generator which excites the circuit.
- (c) Coronal streamers and polar plumes are likely to be filaments produced by the current system.

A more detailed analysis of the circuit, including a computer model of heliospheric currents and magnetic fields has been done by Akasofu, Lee and Gray (1979).

2.2.3 *Magnetospheric circuit.* — Because of the complicated geometry of the magnetosphere, a direct construction of a current model of the magnetosphere

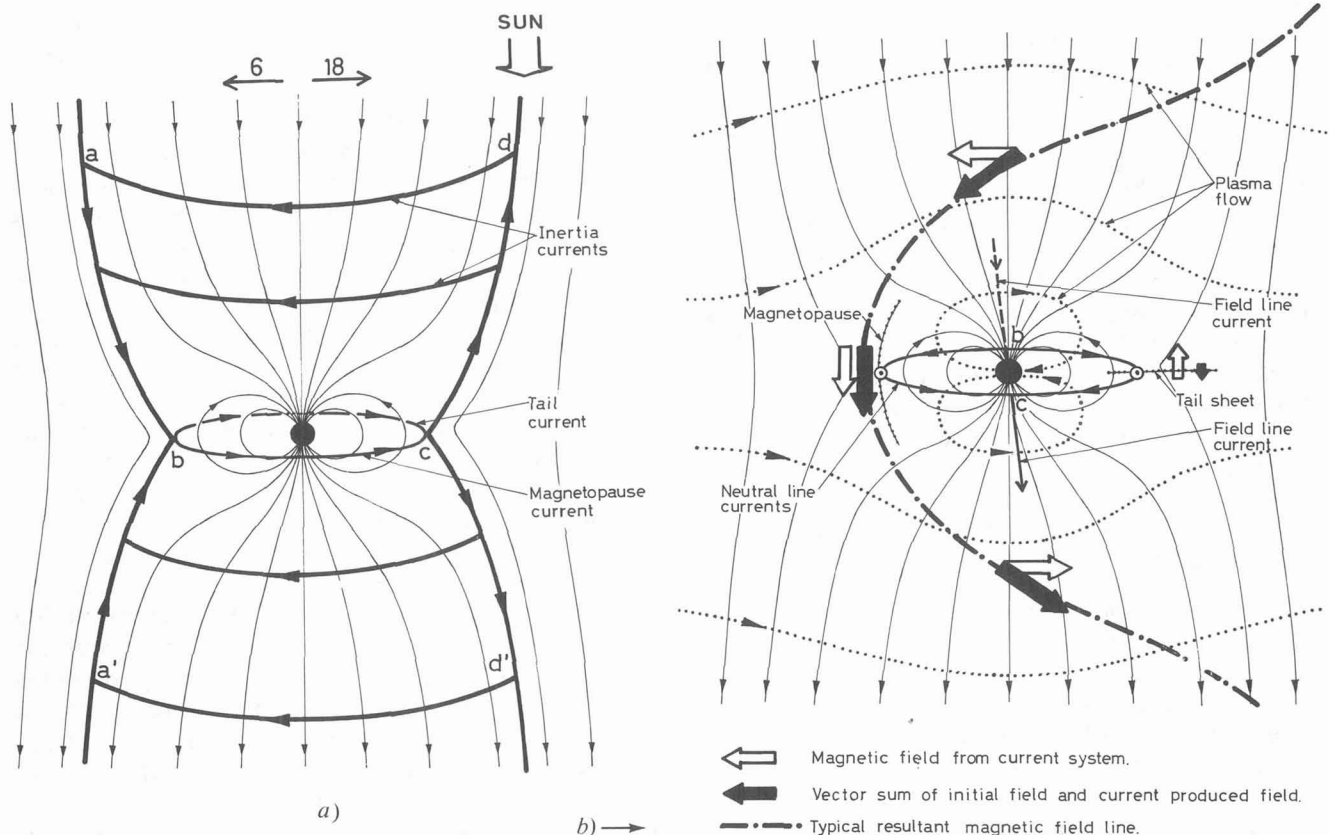


Fig. 12. — Because the magnetospheric circuit has a more complicated geometry than the auroral circuit or the heliospheric circuit, it is more difficult to construct it. Figure 12a shows a *first approximation* in which the magnetic field consists of the earth's dipole field and a homogeneous southward interplanetary field. The solar wind produces an electromotive force, which gives rise to the current system shown in the figure (seen from the sun). If the magnetic field from this current is added to the first approximation field a *second approximation* field is obtained (Fig. 12b), which gives the shape of a typical magnetic field line (— · — · — · —), the magnetopause (· · · · ·) and the tail sheet (· · · · ·). Also the bow shock is derived (not shown in the figure). The current system transfers the kinetic energy of the solar wind to the auroral circuit (which is a part of the large scale circuit) where it produces high energy particles and ultimately ionisation and light in the auroral ionosphere.

is difficult. An attempt has been made to reach such a model by successive approximations (Alfvén and Fälthammar, 1971; Alfvén, 1979). Figure 12a shows the first approximation in which the magnetic field is supposed to be a dipole field superimposed by a southward interplanetary field. The solar wind produces an e.m.f. which gives rise to the current system of figure 12a. If the magnetic field from this is added to the original field we obtain a second approximation (Fig. 12b). The model describes the structure of the magnetopause, the tail current sheet, and the general shape of the magnetic field lines.

Especially important is that the energy transfer from the solar wind to the magnetopause turns out to be a straight-forward and simple process. Further, the auroral circuit of 2.2.1 is part of the circuit, and so is Boström's model of magnetic substorms which can be explained by an exploding double layer formed in the tail current sheet. (*Magnetic merging* theories of magnetic substorms are likely to be erroneous because of neglect of the boundary conditions, see 1.3 and Heikkilä, 1978a, b and Heikkilä and Block, 1977.)

**2.2.4 Current systems of Jupiter, comets and other magnetospheres.** — The conditions in the Jovian magnetosphere are not yet very well clarified. Preliminary results from Pioneer 10 and 11 indicate that the Jovian magnetosphere in some respects is more similar to the heliosphere than the terrestrial magnetosphere. The magnetic field close to Jupiter is a dipole field, but further out there is a strong current in the equatorial plane which to some extent is similar to the heliospheric current in the equatorial plane (Smith, 1979, see Fig. 11). However, the strong asymmetry of the Jovian field and the presence of Io makes the conditions highly asymmetric (Dessler, 1979).

A possible current system in cometary tails has been constructed by Mendis (1978), but unfortunately *in situ* measurements of cometary plasmas are still lacking.

Space measurements from some other magnetospheres may allow the construction of current systems (see i.e. Dolginov, 1978).

**2.2.5 Solar prominence circuit.** — As the sun is still outside the reach of spacecrafts, a detailed diagnostics of solar plasmas is impossible, and theories of solar phenomena will necessarily remain speculative. However we have enough solar observations to be able to extrapolate our knowledge of carefully investigated space plasmas with a rather good confidence (Alfvén, 1977a).

Hence we conclude that a solar prominence is due to a current in a circuit similar to the auroral circuit but simpler: it consists of a magnetic flux tube intersecting the solar surface in two points, and a photospheric or subphoto-spheric connection between these points. The electromotive force is produced by motions in the photosphere in the presence of magnetic

fields. The size of a prominence circuit is comparable to that of the auroral circuit, but the currents are much larger ( $\sim 10^{12}$  A) because of the higher conductivity (the high resistivity in the upper ionosphere is replaced by a low resistivity due to the high temperature).

Like in the auroral circuit a double layer may be produced. The auroral double layer is often rapidly fluctuating, giving rise to the rapid variability of auroral phenomena. The prominence double layer is still more variable; indeed it can explode, producing solar flares. A quantitatively consistent theory of solar flares as due to such a current disruption has been worked out by Carlqvist (1969).

Much work has been spent on attempts to explain solar flares by a magnetic field formalism. (A survey is given by Heyvaerts in his lecture at this conference.) For reasons given in the introduction and in 1.4 (cf. Fig. 2) this is inadequate. More specifically, in the magnetic merging theories of solar flares the boundary conditions are not correctly introduced and hence these theories cannot explain the rapid concentration of the inductive energy of the whole circuit to the point of disruption.

**2.2.6 Possible scaling to galactic dimensions.** — An attempt has been made to scale up the heliospheric current system to galactic dimensions (see 2.5.4).

**2.3 ROTATING MAGNETIZED BODY SURROUNDED BY A PLASMA.** — A basic problem in astrophysics is the interaction between a rotating magnetized body and a surrounding plasma. (The body has of course a gravitational field.) The simplest case is when the magnetization is homogeneous and parallel (or anti-parallel) to the rotational axis.

In the idealized case when only hydromagnetic effects are active, the plasma will attain a Ferraro corotation. However, this is unrealistic for a number of reasons. There is always an outer limit to the corotation because of the limitations of the surrounding plasma. In the case of the Earth the synchronous radius is comparable with the limits of the magnetosphere, outside which we cannot expect corotation. Even closer to the dipole there is a general sunward plasma drift, showing that the corotation is restricted to the plasmasphere. Further out the difference in angular velocity necessarily produces an e.m.f. (which tends to establish corotation) but this is taken up by electrostatic double layers. Hence the double layers produce a *decoupling* which allows a violation of the Ferraro theorem.

In the solar magnetosphere (= heliosphere or interplanetary space) the solar wind prevents the establishment of a corotation. Instead a thin current sheet in the equatorial plane is generated. The heliospheric current system has been discussed in 2.2.2. The knowledge we can gain from studying the transfer of angular momentum to a surrounding plasma should serve as a basis for the approach to the *cos-*

*mogonic problem* how the sun transferred angular momentum to the planets when they were formed and how the planets did the same to their satellite systems. The main difference from the present state is that the plasma density in the surrounding is likely to be much larger. The currents which would be required to establish a Ferraro corotation are so large that they are likely to produce double layers which decouple the surrounding plasma to a certain degree. The state which we should expect (*partial corotation of free-wheeling plasma*) is given by an equilibrium between the gravitation and centrifugal force which because of the geometry of the magnetic field should give the plasma an angular velocity of  $(2/3)^{1/2}$  of the Kepler velocity (see Alfvén and Arrhenius, 1976).

Similar phenomena may be decisive for the evolution of galaxies. The angular momentum of the interstellar medium may be transferred to the intergalactic medium, and its kinetic energy transmitted in plasma cables to the surrounding (Alfvén, 1978a). See 2.5.4.

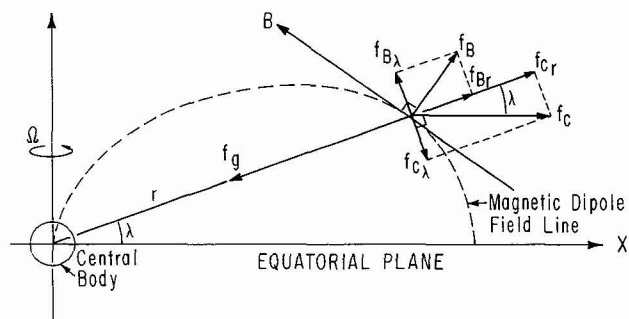


Fig. 13. — Partial corotation.

**2.4 APPLICATION TO COSMOGONY.** — Plasma phenomena were of decisive importance at the origin of the solar system and at the early phases of its evolution. The present chemical and dynamical structure of the planetary and satellite systems is to a large extent a product of such plasma processes.

There are good reasons for believing that the solar system originated from a primeval solar nebula which may have had a very low but certainly not negligible degree of ionization. It is likely to have had a structure which is normal to what all cosmic plasmas seem to have according to Part I; most of its volume was filled by a *passive* plasma which probably was very cool (perhaps 50 K) and very dusty. This was interlaced by a network of *active* plasma regions : current carrying filaments and sheets, which were energized ultimately from the gravitational energy released when the nebula contracted. Their activity was of decisive importance to the dynamical and chemical evolution of the cloud.

There seems to have been three plasma processes which have been essential for the present structure of the solar system.

2.4.1 *Chemical differentiation* at the early phases. This has been discussed in 1.12.

2.4.2 *Critical velocity.* — A very pronounced feature of the solar system is its *band structure* (Fig. 14). For a number of reasons it seemed likely that this was produced when clouds with different chemical composition fell in towards a central body (sun or planet) and were stopped when they reached a certain *critical velocity* given by

$$v_{crit} = \left( \frac{2 e V_{ion}}{m_a} \right)^{1/2}$$

( $V_{ion}$  = ionization potential,  $m$  = atomic mass).

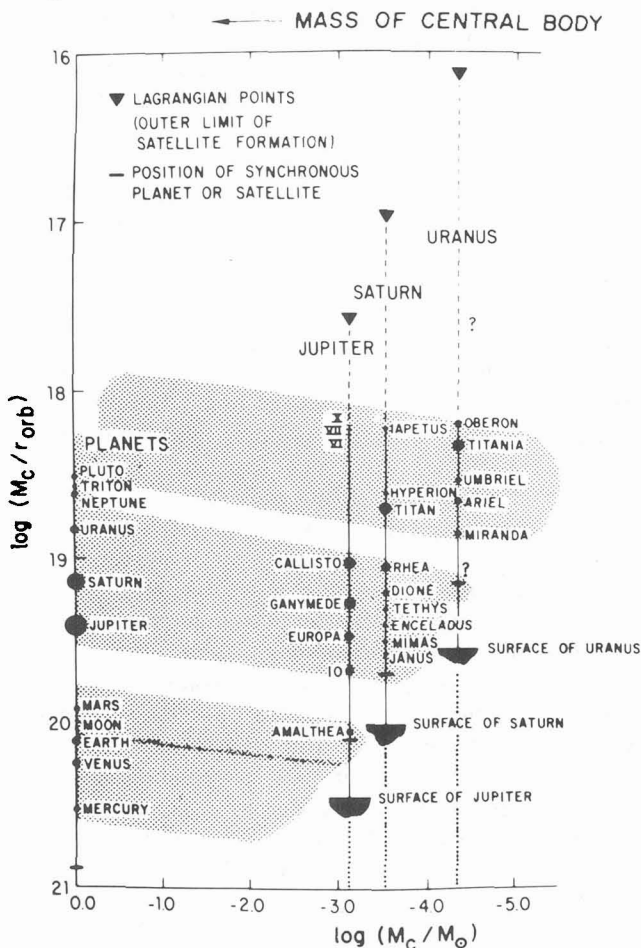


Fig. 14. — Band structure of Solar System.

This theoretical conjecture lacked empirical support, but as soon as the thermonuclear plasma technique became available, experiments were started in order to investigate the theoretically predicted phenomenon. The experiments confirmed the theoretical predictions and led to the discovery of a sharp — actually unexpectedly sharp — limit, given by eq. (2), for the relative velocity between a neutral gas and a magnetized plasma.

The critical velocity has now been subject to extensive experimental and theoretical investigations for



20 years (Danielsson, 1973; Sherman, 1973; Himmel *et al.*, 1973, 1976, 1977; Danielsson and Brenning, 1975; Axnäs, 1978; Raadu, 1978; Piel *et al.*, 1978; Petelski, 1978). It is an example of a plasma phenomenon which was predicted on the basis of a cosmogonic theory which initially was considered to be rather speculative.

There is not yet any unquestionable experimental demonstration of the critical velocity under present cosmical conditions but there are some indications that it has been observed (Srňka, 1977). Experiments to demonstrate the critical velocity under cosmical conditions have been suggested by Möbius, Boswell, Piel and Henry (1979).

**2.4.3 Transfer of angular momentum and partial rotation.** — This is the third plasma phenomenon which probably was of decisive importance for giving our solar system its present structure. See 2.3.

**2.5 COSMOLOGICAL APPLICATIONS.** — **2.5.1 Cellular structure of space and the existence of antimatter.** — A basic cosmological problem is whether the Universe is symmetric with regard to matter-antimatter. As long as the interstellar (and intergalactic) medium was considered to be homogeneous, it was rather difficult to accept the existence of antimatter, because matter and antimatter could not be mixed but must occupy different regions. Theoretically this is possible if there are *Leidenfrost layers* separating regions of antimatter from regions of koinomatter (= ordinary matter). A model of such layers was worked out (Lehnert, 1977, 1978). However, it was not obvious whether such a layer was stable.

The discovery of the cellular structure of space plasmas has drastically changed the situation. We know now that in the magnetospheres there are stable current sheets, separating plasma regions with different magnetization, temperature, density, etc. It is easy to imagine that in principle similar sheets might separate regions of different kinds of matter as shown by Lehnert (1976, 1977).

A Leidenfrost sheet must be surrounded on both the koino- and antimatter side by fully ionized layers, but these are not necessarily more than about one mean free path thick. At that distance there could very well be a sudden transition to a plasma with very low ionization. Such abrupt transitions are often observed in plasma experiments and are well understood theoretically (Lehnert, 1976).

Hence a region of passive koinoplasma and a region of passive antiplasma could coexist close to each other and a cosmically very thin and unnoticeable layer of active plasma will separate them.

**2.5.2 Properties of an ambiplasma.** — The possible existence of antimatter makes the theoretical study of an *ambiplasma* (consisting of a mixture of koinomatter and antimatter) a challenging problem. The plasma should consist not only of protons and

antiprotons but also of high energy ( $10^8$  eV) electrons and positrons.

A thorough analysis of the properties of an ambiplasma (separation of matter and antimatter, production of Leidenfrost-layers, energy release and radiation, etc.) is essential for a deeper understanding of a symmetric Universe.

**2.5.3 Theory of QSOs.** — The enormous energy release in QSOs is one of the headaches in modern astrophysics and a serious difficulty to the Big-Bang hypothesis. As the energy release is much larger than what can reasonably be supplied by nuclear reactions, there are only two energy sources left, viz. gravitation (*black holes*) and annihilation. For a number of reasons the latter alternative seems to be preferable (Alfvén, 1979a, b).

**2.5.4 Double radio sources.** — As one more example of the transfer of knowledge to astrophysics from magnetospheric and laboratory investigations we should mention the problem of double radio sources. The strong synchrotron emission from the pair may either originate from a *hidden* energy source in each of the sources — but no such source has been found — or derive from the galaxy often located exactly half way between the sources — which is more reasonable. However, the mechanism of transfer of energy has been a riddle. Theories about ejection of clouds have met a number of serious difficulties.

It seems that transfer of energy by electric currents of the type we are familiar with in the auroral region may give a solution of this problem. This means that the circuit transferring energy from a generator to a double layer in the laboratory, when scaled up by a linear factor of  $10^9$  explains the transfer of energy to the auroral double layers, and when scaled up again by a similar very large factor may account for the energy transfer to double radio sources (Alfvén, 1978a) (Fig. 15).

**2.6 TRANSFER OF KNOWLEDGE FROM MAGNETOSPHERIC PLASMAS TO LABORATORY PLASMAS.** — Thermonuclear research derives its origin from a transfer of knowledge — or at least inspiration — from cosmical physics. Names like *stellarator* and *astron* testify this. Laboratory physics has generously paid back this debt by introducing new concepts like double layers, current disruption and critical velocity into cosmical physics. Also the current description and the use of circuit diagrams for representing cosmical phenomena of course originate from the laboratory. The rapid development of very sophisticated diagnostics in magnetospheric research may lead us to expect that a transfer of knowledge from cosmical physics to laboratory physics may be fruitful.

Of special interest is that the stability problem which is a major obstacle in thermonuclear research, seems not to be so serious in cosmical physics. Compli-

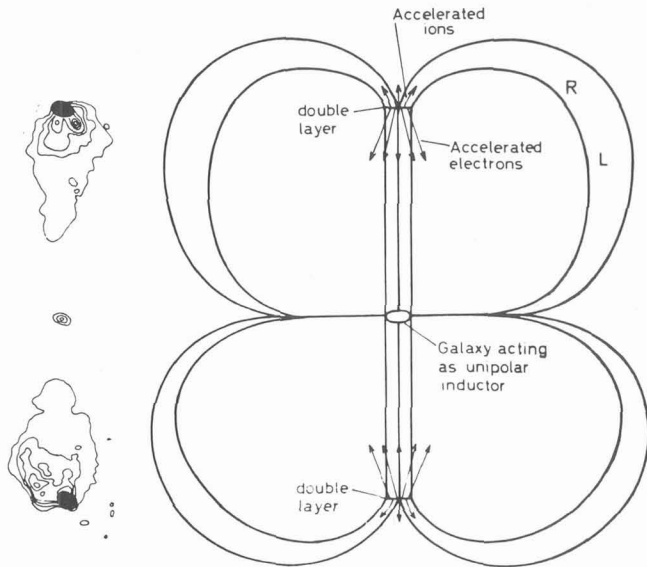


Fig. 15. — Galactic circuit extrapolated from heliospheric circuit. Radio astronomic observations by Current  $10^{17}$  A and double layer voltage  $10^{18}$  V.

ated plasma configurations, like solar prominences, coronal streamers, and the magnetopause seem to be so long-lived that one would guess that they represent stable, or at least semi-stable, configurations.

This may inspire thermonuclear research to consider new approaches to the thermonuclear problem. Further, there are a number of plasma phenomena which are nowadays more easily studied in space than in the laboratory. For example, transients with the electron gyro frequency in a cosmic plasma of  $10^{-4}$  G have a time constant of  $10^{-2}$  s, which is easily measurable — whereas in a thermonuclear plasma of  $10^4$  G it is  $10^{-10}$  s, far below what can be measured in a comfortable way.

So this shows again how important it is to integrate the different domains of plasma physics.

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## References

- AKASOFU, S.-I., What is a Magnetospheric Substorm? *Space Sci. Revs.* for the Chapman Conference, 1979.
- AKASOFU, S.-I., LEE, L. C. and GRAY, P. C., A Model of the Interplanetary Magnetic Field Configuration (private communication) 1979.
- ALFVÉN, H., Electric Current Structure of the Magnetosphere. In *Physics of the Hot Plasma in the Magnetosphere*, B. Hultqvist and L. Stenflo, Ed. (Plenum Publ. Co, New York) 1975a.
- ALFVÉN, H., Relations between Cosmic and Laboratory Plasma Physics, *Ann. of the New York Academy of Sci.* **257** (1975b) 179.
- ALFVÉN, H., Electric Currents in Cosmic Plasmas, *Rev. of Geophys. and Space Phys.* **15** (1977a) n° 3.
- ALFVÉN, H., Is the Universe Matter-Antimatter Symmetric? *Antinucleon-Nucleon Interactions*, Wenner-Gren Volume 29, G. Ekspong and S. Nilsson, Ed. (Pergamon Press, Oxford and New York) 1977b.
- ALFVÉN, H., Double Radio Sources, *Astrophys. Sp. Sci.* **54** (1978a) 279.
- ALFVÉN, H., The Band Structure of the Solar System. In *The Origin of the Solar System*, S. F. Dermott, Ed. (J. Wiley, New York), 1978b.
- ALFVÉN, H., Electric Current Model of Magnetosphere, TRITA-EPP-79-09, Royal Inst of Technology, Stockholm and in Proceedings of the Chapman Conference on Magnetospheric Boundary Layers, Alpbach June 11-15, 1979 (to be published by European Space Agency), 1979a.
- ALFVÉN, H., Annihilation Model of the QSOs, TRITA-EPP-79-08, Royal Inst. of Technology, Stockholm (to be published in *Astrophys. Space Sci.*) 1979b.
- ALFVÉN, H. and ARRHENIUS, G., Evolution of the Solar System, NASA SP-345, Washington D.C., 1976.
- ALFVÉN, H., ARRHENIUS, G. and MENDIS, D. A., The Role of Plasma in the Primeval Nebula. In *Comets, Asteroids, Meteorites, Interrelations, Evolution and Origins*. Proc. 39th Int. Coll. IAU, Lyon, France 1976, Univ. of Toledo, Ohio, USA 1977, 1976.
- ALFVÉN, H. and CARLQVIST, P., Interstellar Clouds and the Formation of Stars, *Astrophys. Space Sci.* **55** (1978) 487.
- ALFVÉN, H. and FÄLTHAMMAR, C.-G., *Cosmical Electrodynamics*. Int. Series of Monographs on Physics (Clarendon Press, Oxford), 1963.
- ALFVÉN, H. and FÄLTHAMMAR, C.-G., A New Approach to the Theory of the Magnetosphere, *Cosmic Electrodynamics* **2** (1971) 78.
- ARRHENIUS, G., Chemical Aspects of the Formation of the Solar System. In *Origin of the Solar System*, S. F. Dermott, Ed. (J. Wiley, New York), 1976, p. 522.
- AXNÄS, I., Experimental Investigations of the Critical Ionization Velocity in Gas Mixtures, *Astrophys. Space Sci.* **55** (1978a) 139.
- AXNÄS, I., Experimental Comparison of the Critical Ionization Velocity in Atomic and Molecular Gases, TRITA-EPP-78-04, Royal Inst. of Technology, Stockholm, 1978b.
- BATTRICK, B., Proc. of the Chapman Conference on Magnetospheric Boundary Layers, Alpbach, June 11-15, 1979 (to be published by European Space Agency), 1979.
- BLOCK, L. P., Interpretation of Laboratory Experiments of Interest to Space Physics. Proc. AGU Int. Symp. on Solar-Terrestrial Phys., Boulder, Col., 1976, D. J. Williams, Ed. (Am. Geophys. Union), 1976, p. 255.

- BLOCK, L. P., A Double Layer Review, *Astrophys. Space Sci.* **55** (1978) 59.
- BLOCK, L. P. and FALTHAMMAR, C.-G., Effects of Field-Aligned Currents on the Structure of the Ionosphere, *J. Geophys. Res.* **73** (1968) 4807.
- BLOCK, L. P. and FALTHAMMAR, C.-G., Mechanisms that May Support Magnetic-Field-Aligned Electric Fields in the Magnetosphere, *Ann. Geophys.* **32** (1976) 161.
- BOSTRÖM, R., Ionosphere-Magnetosphere Coupling. In *Magnetospheric Physics*, B. M. McCormac, Ed. (D. Reidel Publ. Co, Dordrecht, Holland), 1974, p. 45.
- BOSTRÖM, R., Mechanisms for Driving Birkeland Currents. In *Physics of the Hot Plasma in the Magnetosphere*, B. Hultqvist and L. Stenflo, Ed. (Plenum Press, New York), 1975.
- CARLQVIST, P., Current Limitation and Solar Flares, *Solar Physics* **7** (1969) 377.
- CARLQVIST, P., On the Formation of Double Layers in Plasmas, *Cosmic Electrodynamics* **3** (1972) 377.
- CARLQVIST, P., Double Layers and Two-Stream Instability in the Solar Flares, TRITA-EPP-73-05, Royal Inst. of Technology, Stockholm, 1973.
- CARLQVIST, P., Some Theoretical Aspects of Electrostatic Double Layers, TRITA-EPP-78-15, Royal Inst. of Technology, Stockholm (to be published in Wave Instabilities in Space Plasmas, URSI XIX General Assembly, Astrophys. Space Science Book Series (Reidel Publ. Co.), 1979) 1978.
- CLARK, W. H. M. and HAMBERGER, S. M., Anomalous Conductivity and Electron Heating in a Plasma Unstable to the Two-Stream Instability, CLM-P531, Culham Lab., Abingdon, Oxfordshire, England, 1979.
- COAKLEY, P., JOHNSON, L. and HERSHKOWITZ, N., Strong Laboratory Double Layers in the Presence of a Magnetic Field, *Phys. Lett.* **70A** (1979) 425.
- DANIELSSON, L., Review of the Critical Velocity of Gas-Plasma Interaction. I : Experimental Observations. *Astrophys. Space Sci.* **24** (1973) 459.
- DANIELSSON, L. and BRENNING, N., Experiment on the Interaction between a Plasma and a Neutral Gas II, *Phys. Fluids* **18** (1975) 661.
- DANIELSSON, L. and LINDBERG, L., Plasma Flow through a Magnetic Dipole Field, *Phys. Fluids* **7** (1964) 1878.
- DANIELSSON, L. and LINDBERG, L., Experimental Study of the Flow of a Magnetized Plasma through a Magnetic Dipole Field, *Arkiv för Fysik* **28** (1965) 1.
- DESSLER, A. J., Comparison of Voyager Flyby Data with the Magnetic-Anomaly Model of Jupiter-Magnetopause Effects. Proc. of the Chapman Conference on Magnetospheric Boundary Layers, Alpbach, June 11-15, 1979 (to be published by European Space Agency), 1979.
- DOLGINOV, S. S., Magnetic Fields in the Vicinity of Venus According to « Venera » and « Mariner » Data, report presented at the Symp. on the Origin of Planetary Magnetism, Houston, Texas, USA, Nov. 8-11, 1978.
- DUNGEY, J. W., Interplanetary Magnetic Field and the Auroral Zones, *Phys. Rev. Lett.* **6** (1961) 47.
- DUNGEY, J. W., Null points in Space Plasma. In Proc. Plasma Space Sci. Symp., C. C. Chang and S. S. Huang, Ed. (D. Reidel Publ. Co, Dordrecht, Holland), 1965.
- EATHER, R. H., MENDE, S. B. and WEBER, E. J., Cusp Aurora and Substorm Current Systems. Proc. of the Chapman Conference on Magnetospheric Boundary Layers, Alpbach, June 11-15, 1979 (to be published by European Space Agency), 1979.
- FALTHAMMAR, C.-G., Laboratory Experiments of Magnetospheric Interest, *Space Sci. Rev.* **15** (1974) 803.
- FALTHAMMAR, C.-G., Problems Related to Macroscopic Electric Fields in the Magnetosphere, *Rev. Geophys. and Space Phys.* **15** (1977) n° 4, 457.
- FALTHAMMAR, C.-G., Generation Mechanisms for Magnetic-Field-Aligned Electric Fields in the Magnetosphere, *J. Geomag. Geoelectr.* **30** (1978a) 419.
- FALTHAMMAR, C.-G., Non-Resistive Electric Potential Drops in Cosmical Plasmas, TRITA-EPP-78-17, Royal Inst. of Technology Stockholm, 1978b.
- FALTHAMMAR, C.-G., AKASOFU, S.-I. and ALFVÉN, H., The Significance of Magnetospheric Research for Progress in Astrophysics, *Nature* **275** (1978) 185.
- GURNETT, D. A., Electric Field and Plasma Observations in the Magnetosphere. In *Critical Problems of Magnetospheric Physics*, E. R. Dyer, Ed., p. 123, Inter-Union Committee on Solar-Terrestrial Physics, National Academy of Sciences, Washington, D.C., USA, 1972.
- HEIKKILA, W. J., Magnetospheric Plasma Regions and Boundaries. In *Physics of the Hot Plasma in the Magnetosphere*, B. Hultqvist and L. Stenflo, Ed. (Plenum Publ. Co, New York), 1975.
- HEIKKILA, W. J., Criticism of Reconnection Models of the Magnetosphere, *Planet. Space Sci.* **26** (1978a) 121.
- HEIKKILA, W. J., Electric Field Topology Near the Dayside Magnetopause, *J. Geophys. Res.* **83** (1978b) 1071.
- HEIKKILA, W. J., BLOCK, L. P., Review of Magnetospheric Boundary Layer Phenomena and Relations to Current Theories, *Geophysica*, **14** : 2 (1977).
- HIMMEL, G. and PIEL, A., The Velocity Limitation in a Rotating Plasma Device of the Homopolar Type, *J. Phys. D : Appl. Phys.* **6** (1973).
- HIMMEL, G., MOBIUS, E. and PIEL, A., Investigation of the Structure and the Plasma Parameters in a Critical Velocity Rotating Plasma, *Z. Naturforsch.* **31a** (1976) 934.
- HIMMEL, G., MOBIUS, E. and PIEL, A., Investigation of Particle Velocities in a Critical Velocity Rotating Plasma, *Z. Naturforsch.* **32a** (1977) 577.
- KAN, J. R., AKASOFU, S.-I. and LEE, L. C., Physical Processes for the Onset of Magnetospheric Substorms, *Space Sci. Rev.*, for the Chapman Conference on Magnetospheric Substorms, 1978.
- KAWASHIMA, N., Characteristics of Intruding Plasma in a Simulated Magnetosphere, *Cosmic Electrodynamics* **1** (1971) 415.
- LEHNERT, B., Element Separation Effects in the Boundary Region of a Plasma Surrounded by Neutral Gas, *Astrophys. Space Sci.* **40** (1976) 225.
- LEHNERT, B., Problems of Matter-Antimatter Boundary Layers, *Astrophys. Space Sci.* **46** (1977) 61.
- LEHNERT, B., Matter-Antimatter Boundary Layers with a Magnetic Neutral Sheet, *Astrophys. Space Sci.* **53** (1978) 459.
- LENNARTSSON, W., On the Role of Magnetic Mirroring in the Auroral Phenomena, *Astrophys. Space Sci.* **51** (1977) 461.
- MARKLUND, G., Steady State Models for Filamentary Plasma Structures Associated with Force-Free Magnetic Fields, TRITA-EPP-78-09, Royal Inst. of Technology, Stockholm, 1978.
- MARKLUND, G., Plasma Convection in Force-Free magnetic Fields as a Mechanism for Chemical Separation in Cosmical Plasmas, *Nature* **277** (1979) 370.
- MENDIS, D. A., On the Hydromagnetic Model of Comets, *The Moon, and the Planets*, **18** (1978) 361.
- MOTLEY, R. W., *Q-Machines* (Academic Press, New York), 1975.
- MOZER, F. S., CARLSON, C. N., HUDSON, M. K., TORBERT, R. B., PARADY, B., YATTEAU, J. and KELLEY, M. C., Observations of Paired Electrostatic Shocks in the Polar Magnetosphere, *Phys. Rev. Lett.* **38** (1977) 292.
- MOBIUS, E., PIEL, A. and HIMMEL, G., Evaluation of the Plasma-parameters and the Nonthermal Field Fluctuations in a Critical Velocity Rotating Plasma, Report 78-M2-036, Inst. für Experimentalphysik II, Ruhr-Universität Bochum, 1978.
- MOBIUS, E., PIEL, A. and HIMMEL, G., Determination of the Plasma-parameters and the Suprathermal Microfields in a Critical Velocity Rotating Plasma, *Z. Naturforsch.* **34a** (1979a).
- MOBIUS, E., BOSWELL, R. W., PIEL, A. and HENRY, D., A Spacelab Experiment on the Critical Ionization Velocity, *Geophys. Res. Lett.* **6** (1979b) 29.

- PETELSKI, E., Critical Ionization Velocity and the Interaction of Stellar Winds with the Stellar Medium. IVth Solar Wind Conf., Burghausen, Germany 1978.
- PIEL, A., MOBIUS, E. and HIMMEL, G., The Origin of Turbulent Heating in a Critical Velocity Rotating Plasma, Report 78-M2-037, Inst. für Experimentalphysik II der Ruhr-Universität Bochum, 1978.
- PODGORNY, I. M. and SAGDEEV, R. Z., Physics of Interplanetary Plasma and Laboratory Experiments, *Soviet Phys. Uspekhi* **12** (1970) 445.
- PODGORNY, I. M., Laboratory Experiments (Plasma Intrusion into the Magnetic Field), In Proc. Int. Symp. on Solar-Terrestrial Physics, Boulder, Colorado, June 7-18, 1976.
- RAADU, M., The Role of Electrostatic Instabilities in the Critical Velocity Mechanism, *Astrophys. Space Sci.* **55** (1978) 125.
- ROSTOKER, G. and BOSTROM, R., A Mechanism for Driving the Gross Birkeland Current Configuration in the Auroral Oval, *J. Geophys. Res.* **81** (1976) 235.
- RUSSELL, C. T., ELPIC, R. C. and SLAVIN, J. A., The Solar Wind Interaction with Venus. Proc. on the Chapman Conf. on Magnetospheric Boundary Layers, Alpbach, June 11-15, 1979 (to be published by European Space Agency), 1979.
- SCHOLER, M., HOVESTADT, D., KLECKER, B. and GLOEKLER, G., The Composition of Energetic Particles in Corotating Events, *Astrophys. J.* **227** (1979) 323.
- SHAWHAN, S. D., FALTHAMMAR, C.-G. and BLOCK, L. P., On the Nature of Large Auroral Zone Electric Fields at 1-R<sub>E</sub> Altitude, *J. Geophys. Res.* **83** (1978) 1049.
- SHERMAN, J. C., Review of the Critical Velocity of Gas-Plasma Interaction II : Theory. *Astrophys. Space Sci.* **24** (1973) 487.
- SISCOE, G. L., Scaling Relations and Planetary Magnetospheres. In Proc. of the Chapman Conf. on Magnetospheric Boundary Layers, Alpbach, June 11-15, 1979 (to be published by European Space Agency), 1979.
- SMITH, E., Jupiter's Magnetosphere. In Proc. of the Chapman Conf. on Magnetospheric Boundary Layers, Alpbach, June 11-15, 1979 (to be published by European Space Agency), 1979.
- SRNKA, L. J., *Critical velocity and the LTP. Phys. Earth Planet. Inter.* **14** (1977) 321.
- TORVÉN, S., Formation of Double Layers in Laboratory Plasmas, TRITA-EPP-78-13, Royal Inst. of Technology, Stockholm (to be published in Wave Instabilities in Space Plasmas, URSI XIX General Assembly, Astrophys. and Space Sci. Book Series (Reidel Publ. Co.) 1979 1979, 1978.
- TORVÉN, S. and ANDERSSON, D., Observations of Electric Double Layers in a Magnetized Plasma, *J. Phys. D. : Appl. Phys.* **12** (1979) 717.
- ZMUDA, A. J. and ARMSTRONG, J. C., The Diurnal Flow Pattern of Field-Aligned Currents, *J. Geophys. Res.* **79** (1974) 4611.