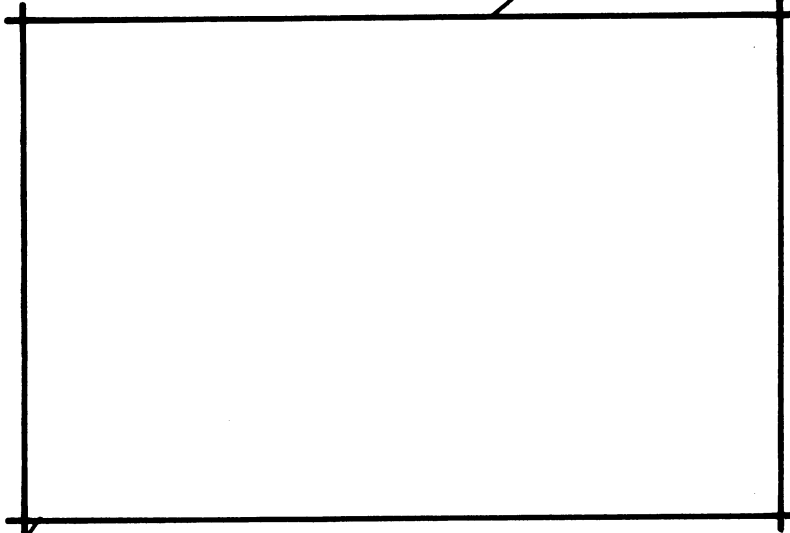


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DOUBLE LAYERS AND CIRCUITS IN  
ASTROPHYSICS

Hannes Alfvén

May 1986

Opening lecture at the "Double Layers in  
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# DOUBLE LAYERS AND CIRCUITS IN ASTROPHYSICS

by Hannes Alfvén

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## DOUBLE LAYERS AND CIRCUITS IN ASTROPHYSICS

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### Abstract

As the rate of energy release in a double layer with voltage  $\Delta V$  is  $P \approx I\Delta V$ , a double layer must be treated as a part of a circuit which delivers the current  $I$ . As neither double layer nor circuit can be derived from magnetofluid models of a plasma, such models are useless for treating energy transfer by means of double layers. They must be replaced by particle models and circuit theory.

A simple circuit is suggested which is applied to the energizing of auroral particles, to solar flares, and to intergalactic double radio sources. Application to the heliospheric current systems leads to the prediction of two double layers on the sun's axis which may give radiations detectable from earth.

Double layers in space should be classified as a new type of celestial object (one example is the double radio sources). It is tentatively suggested in X-ray and  $\gamma$ -ray bursts may be due to exploding double layers (although annihilation is an alternative energy source).

A study of how a number of the most used textbooks in astrophysics treat important concepts like double layers, critical velocity, pinch effects and circuits is made. It is found that students using these textbooks remain essentially ignorant of even the existence of these, in spite of the fact that some of them have been well known for half a century (e.g., double layers, Langmuir, 1929; pinch effect, Bennet, 1934). The con-

clusion is that astrophysics is too important to be left in the hands of those astrophysicist who have got their main knowledge from these textbooks. Earth bound and space telescope data must be treated by scientists who are familiar with laboratory and magnetospheric physics and circuit theory, and of course with modern plasma theory. It should be remembered that at least by volume the universe consists to more than 99% of plasma, and that electromagnetic forces are  $10^{39}$  time stronger than gravitation.

## I GENERAL PROPERTIES OF DOUBLE LAYERS

### A. Double Layers as a Surface Phenomenon in Plasmas

Since the time of Langmuir, we know that a double layer is a plasma formation by which a plasma - in the physical meaning of this word - protects itself from the environment. It is analogous to a cell wall by which a plasma - in the biological meaning of this word - protects itself from the environment.

If an electric discharge is produced between a cathode and an anode (Fig. 1) there is a double layer, called a cathode sheath, produced near the cathode, which accelerates electrons which carry a current through the plasma. Similarly, a double layer is set up near the anode, protecting the plasma from this electrode. Again, a space charge constitutes the border between the double layer and the plasma. All these double layers carry electric currents.

The lateral limitation of the plasma is also produced by double layers, which reduce and slow down the escape of the rapid electrons and accelerates the positive ions outwards so that an ambipolar diffusion is established (no net currents). If the plasma is enclosed in a vessel, its walls get a negative charge and a positive space charge is set up which - again - is the border between the double layer and the plasma. If the discharge constricts itself the walls can be taken away (without removing the space charge they carry). In these double layers the net electric current is zero.

If the cathode itself emits electrons, e.g., if it is a thermionic or photoelectric emitter, the sign of the cathode fall may be reversed, so that the double layer is limited by a negative space charge which acts as a "virtual cathode". The anode fall may also be reversed.

The lateral double layers may also change sign. This occurs in a dusty plasma if the dust is negatively charged (e.g., by absorbing most of the electrons). In this case we have a "reversed plasma" in which the ions form the lighter component. A magnetized plasma in which the Larmor radius of the ions is much larger than that of the electrons may also be a reversed plasma.

If a plasma is inhomogeneous so that the chemical composition, density, and/or electron temperature differs in different parts of the plasma, the plasma may set up double layers which split the plasma into two or more regions, each of which becomes more homogeneous (Schönhuber, 1968). For example, a Birkeland current flowing between the ionosphere and the magnetosphere may produce one or more double layers in this way, when it flows through regions with different densities.

There are innumerable variations and complications of the simple case we have discussed, in the same way as biological cell walls show innumerable variations. If we try to increase the current by increasing the applied voltage, the plasma may produce a double layer (see Fig. 1) which takes up part of the voltage so that the plasma current density does not exceed a certain value. Hence the plasma divides itself into two cells, analogous to what a biological cell does when it gets a large energy input.

The voltage difference  $\Delta V$  over a double layer is usually of the order 5-10 times the equivalent of the temperature energy  $kT_e/e$  (Torvén and Andersson, 1979). However, if there are two independent plasmas produced by different sources, the double layer which is set up at the border between them may be 100 or 1000  $kT_e/e$  or even larger (Sato et al., 1981; Torvén, 1982).



## B. Noise in Double Layers

There is one property of a double layer which often is neglected: a double layer very often - perhaps always - produces noise and fluctuations. By this we mean irregular rapid variations within a broad band of frequencies. Lindberg (1982) studied the noise in a stationary fluctuating double layer and demonstrated that it broadens the energy spectrum of the electrons. The plasma may expand perpendicular to the magnetic field. The electrons in the beam which is produced in the double layer are scattered much more by the noise than by collisions. (Some people claim that noise is essential for the formation and sustenance of a double layer. This is actually a chicken-egg problem.)

An analogy to this is that the "critical velocity" phenomenon also seems to be associated with noise. Noise production is often associated with strong currents through plasmas. Langmuir (1927) proposed that random impulses strongly scatter electrons in gas discharges, an early example of the importance of noise in determining the behaviour of a plasma.

The noise - often incorrectly called "turbulence" - is such an important property of plasmas that theories which do not take it into consideration run some risk of being irrelevant. In additions, computer simulations that do not produce noisy double layers should be regarded with some scepticism.

The development of three-dimensional electromagnetic computer simulations (Buneman et al., 1980) will allow a much more realistic treatment of plasma behaviour. Peratt et al. (1980) have thus been able to simulate in detail experiments on the interaction of two plasma filaments produced by exploding wires. Both electrostatic and electromagnetic fluctuations are implicitly included.

### C. Theoretical and Experimental Approaches

Since thermonuclear research started with Zeta, Tokamaks, Stellarators - not to forget the Perhapsastron - plasma theories have absorbed a large part of the energies of the best physicists of our time. The progress which has been achieved is much less than was originally expected. The reason may be that from the point of view of the traditional theoretical physicist, a plasma looks immensely complicated. We may express this by saying that when, by an immense number of vectors and tensors and integral equations, theoreticians have prescribed what a plasma must do, the plasma - like a naughty child - refuses to obey. The reason is either that the plasma is so silly that it does not understand the sophisticated mathematics, or it is that the plasma is so clever that it finds other ways of behaving, ways which the theoreticians were not clever enough to anticipate. Perhaps the noise generation is one of the nasty tricks the plasma uses in its IQ competition with the theoretical physicists.

One way out of this difficulty is to ask the plasma itself to integrate the equations; in other words, to make plasma experiments. Confining ourselves to cosmic plasmas, nowadays there are two different ways of doing this.

1. By performing scale model experiments in the laboratory. This requires a sophisticated technique, which in part we can borrow from the thermonuclear plasma physicists. It also requires methods to "translate" laboratory results to cosmic situations. (See CP, I.2 \*). Great progress has been made in this respect, but much remains to be done.

2. By using space as a laboratory and performing the experiments in space. This is a fascinating new technology which is most promising - but somewhat more expensive. We shall shortly discuss the laboratory experiments in later sections. There are a number of good surveys on the program of this meeting.

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\*) CP stands for H. Alfvén, 1981.

#### D. Field and Particle Aspects of Plasmas

Space measurements of magnetic fields are relatively easy, whereas direct measurements of electric currents are very difficult - in many cases impossible. (Roy Torbert (1985) is now developing a technique which makes direct measurements of space currents possible). Hence, it is natural to present the results of space exploration (from spacecraft and from astrophysical observations) with pictures of the magnetic field configuration. Furthermore, in magnetohydrodynamic theories it is convenient to eliminate the current ( $i$  = current density) by  $\nabla \times B$ . 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 which require an approach in which the electric current is taken account of explicitly. The translation between the magnetic field description and the electric current description is made with the help of Maxwell's first equation

$$\nabla \times B = \mu_0 \left( i + \frac{\delta D}{\delta t} \right) \quad (1)$$

in which the displacement current can usually be neglected. (However, it is sometimes convenient to account for the kinetic energy of a magnetized plasma by introducing the permittivity  $\epsilon = \epsilon [1 + (c/V_{MH})^2]$ , where  $c$  and  $V_{MH}$  are the velocities of light and of hydromagnetic waves (see Alfvén and Fälthammar, 1963, Cosmical Electrodynamics 3.4.4, hereafter referred to as CE. If this formalism is used, the displacement current is often large).

Phenomena which cannot be understood without explicitly accounting for the current are:

- 1) Formation of double layers.

- 2) The occurrence of explosive events such as solar flares, magnetic substorms, possibly also "internal ionization" phenomena in comets (Wurm, 1963; Mendis, 1978) and stellar flares.
- 3) Double layer violation of the Ferraro corotation. Establishing "partial corotation" is essential for the understanding of some cosmogonic processes (H. Alfvén and G. Arrhenius, 1975 and 1976).
- 4) Formation of filaments in the solar atmosphere, in the ionosphere of Venus and in the tails of comets and in interstellar nebulae.
- 5) Formation of current sheets which may give space a "cellular structure".

Exploration of those plasma properties which can be described by the magnetic field concept have in general been successful. However, this is not the case for those phenomena which cannot be understood by this approach.

#### E. Recent Advances

There is a rapidly growing literature concerning double layers and their importance for different cosmic situations. Of special interest is the work of Knorr and Goertz (1974), Block (1978) and Sato and Okuda (1980, 1981). A balanced review of these achievements is given by Smith (1983).

As indicated by the title of the present lecture, I will concentrate my attention on the astrophysical applications of double layer theory. The development of the theory of double layers, including numerical simulation, is covered by a number of other papers at this meeting.

## II. LABORATORY EXPERIMENTS

### A. Electrical Discharges in Gases

Towards the end of the nineteenth century electric discharges in gases began to attract increased interest. They were studied in Germany and in England. As there were few international conferences, the Germans and the English made the same discoveries independently. Later, a strong group in Russia was also active. The best survey of the early development is Engel-Steenbeck, Elektrische Gasentladungen (1932). See also Cobine (1958). Some modern textbooks are those by Loeb (1961), Papoular (1963), and Cherrington (1974).

### B. Birkeland

At the turn of the century geophysicists began to be interested in electrical discharges, because it seemed possible that the aurora was an electrical discharge. Anyone who is familiar with electrical discharges in the laboratory and observes a really beautiful aurora cannot avoid noting the similarity between the multi-colored flickering light in the sky and in the laboratory. Birkeland was the most prominent pioneer. He made his famous terrella experiment in order to investigate this possibility (Birkeland, 1908). Based on his experiments, and on extensive observations of aurora in the auroral region he proposed a current system which is basically the same as is generally accepted today. However, the theory of electric discharges was still in a very primitive state.

When Sydney Chapman began his investigations on magnetic storms and aurora one or two decades later, he proposed a current system (the Chapman and Vestine system (Chapman and Vestine, 1938)) which was located entirely in the ionosphere. His most important argument against Birkeland's current system was that above the atmosphere there was a vacuum, and hence there could be no electrons or ions which could carry any currents.

(The relation between Chapman and Birkeland is analyzed by Dessler (1983).)

### C. Langmuir and Plasma

The interest in double layers made a great leap forward when Langmuir began his investigations. He introduced the term plasma in this paper "Oscillations in Ionized Gases" (Langmuir, 1928; see also Langmuir and Tonks, 1929a and b). Curiously enough, he does not give any motivation for choosing this word, which was probably borrowed from medical terminology. He just states: "We shall use the name "plasma" to describe this region containing balanced charges of ions and electrons". His biographers do not give any explanation either. Langmuir also made the first detailed analyses of double layers.

Irving Langmuir was probably the most fascinating man of the plasma pioneers. As his biographers describe him, he was far from being a narrow-minded specialist. His curiosity was all-embracing, his enthusiasm indiscriminate. He liked whatever he looked upon, and he looked everywhere. Indeed he was not far from the ideal which Roederer, in a recent paper (1985), contrasts with the isolated specialists that dominate science today (see Section VIII).

Langmuir once wrote, "Perhaps my most deeply rooted hobby is to understand the mechanism of simple and familiar phenomena" and the phenomena might be anything from molecules to mountains. One of his friends said, "Langmuir is a regular thinking machine: put in facts and you get out a theory". And the facts his always active brain combined were anything from electrical discharges and plasmas to biological and geophysical phenomena. Science as fun was one of his cardinal tenets.

From this one gets the impression that he was very superficial. This is not correct. He got a Nobel prize in chemistry because he was recognized as the father of surface chemistry. He knew

enough of biology to borrow the term plasma from this science, and the mechanism of double layers from surface chemistry. Langmuir's probes were of decisive value for the early exploration of plasmas and double layers, and they are still valuable tools.

All magnetospheric physicists must regret that as far as is known, he probably never saw a full-scale auroral display. Schenectady, where he spent most of his life is rather far from the auroral zone, and he seems never to have travelled to the auroral zone. If he had, his passion for combining phenomena in different fields might very well have made him realize that the beautiful flickering multi-colored phenomena in the sky must be connected with the beautiful flickering multi-colored phenomena he had observed so many times in his discharge tubes. At a time when Birkeland was dead he might have saved magnetospheric physics from half a century when it was a credo that the road to magnetic storms and aurorae should go through a jungle of misleading mathematical formulae where trees and trees prevented you from seeing the wood - but you can never reconstruct history.

In 1950 I published a monograph, Cosmical Electrodynamics (Alfvén, 1950) in which Chapter III deals with electrical discharges in gases. Essential parts of this is devoted to plasma physics, I mention Langmuir only in passing because a quarter of a century after his break-through the results were considered as "classical": all experimental physicists were familiar with his works on plasmas, double layers, probes, etc. However, many theoreticians were not; they had no knowledge of Langmuir's work. They do not mention the word "plasma" and had no idea that experiments in close contact with theory had shown that plasmas were drastically different from their "ionized gases". I tried to draw attention to this by pointing out: "What is urgently needed is not a refined mathematical treatment (referring to Chapman-Cowling) but a rough analysis of the basic phenomena (referring to the general knowledge of plasmas).

Today, 60 years after Langmuir most astrophysicists still have no knowledge of his work. The velocity of the spread of relevant knowledge to astrophysics seems to be much below the velocity of light (compare Section VIII).

D. The Energy Situation in Sweden and Exploding Double Layers

In Sweden the waterpower is located in the north, and the industry in the south. The transfer of power between these regions over a distance of about 1000 km was first done with a.c. When it was realized that d.c. transmission would be cheaper and that this also could be used in underwater cables, mercury rectifiers were developed. It turned out that such a system normally worked well, but it happened now and then that the rectifiers produced enormous overvoltages, so that fat electric sparks filled the rectifying station and did considerable harm. In order to get rid of this a collaboration started between the rectifier constructors and some plasma physicists at the Royal Institute of Technology in Stockholm.

An arc rectifier must have a very low pressure of mercury vapor in order to stand the high back voltages during half of the a.c. cycle. On the other hand, it must be able to carry large currents during the other half-cycle. It turned out that these two requirements were conflicting, because at a very low pressure the plasma could not carry enough current. If the current density is too high, an exploding double layer may be formed. This means that in the plasma an evacuated region is produced: the plasma refuses to carry any current at all. At the sudden interruption a some 100 or 1000 km inductance produces enormous over-voltages, which may be destructive.

In order to clarify this phenomenon a series of laboratory experiments was made, in close contact with theoretical work on the same phenomenon. Nicolai Herlofson was the leader of this activity.



At low current densities a drift motion  $v_d < v_T$  is superimposed on the thermal velocity  $v_T$  of the electrons in the plasma. If the current density increases so that  $v_d > v_T$  the motion becomes more similar to a beam, and an instability sets in which is related to the two-stream instability. This produces a double layer which may be relatively stable (although it often is noisy and may move along the tube). If the voltage over the tube is increased in order to increase the current, the higher voltage is taken up by the double layer and the current is not increased. However, under certain conditions the double layer may "explode".

A simple mechanism of explosion is the following: the double layer can be considered as a diode for electrons combined with a reverse diode for ions, limited by a slab of plasma on the cathode side and another slab on the anode side. Electrons starting from the cathode get accelerated in the diode and impinge upon the anode slab with a considerable momentum which they transfer to the plasma. Similarly, accelerated ions transfer momentum to the cathode slab. When more energy is supplied from the outer circuit the result is that the anode and cathode plasma columns are pushed away from each other. When the distance between the electrons in the diodes becomes larger the drop in voltage increases. This run-away phenomenon leads to an explosion.

Nowadays the mercury arc rectifiers are replaced by semiconductors, but our work with them led to an interesting spin-off in cosmic physics. We had since long been interested in solar physics and had interpreted solar prominences as caused by pinching electric currents. With this as background, Jacobsen and Carlquist (1964) suggested that the violent explosions called solar flares were produced by the same basic mechanism as made the mercury arc rectifiers explode. It drew attention to the fact that every inductive circuit carrying a current is intrinsically explosive.

Further consequences were:

1. The obvious connection between laboratory and space plasma led to a long series of plasma experiments planned to clarify cosmic phenomena.
2. It inspired Carlqvist to work out a detailed theory of solar flares, and later to develop a theory of relativistic DL's.
3. It inspired Boström (1976) to develop a theory of magnetic substorms, which in important respects is similar to Akasofu's theory (Akasofu, 1977).

In general, the connection between a technical difficulty and an astrophysical phenomenon led to what Roederer (1985) calls an "interdisciplinarification", which turned out to be very fruitful.

#### E. Extrapolation to Relativistic Double Layers

In most of the DL's in the magnetospheres and those studied so far in the laboratory the electrons and ions have such low energies that relativistic effects are usually not very important. However, in solar flares DL's with voltages of  $10^9$  V or even more may occur, and in galactic phenomena we may have voltages which are several orders of magnitude larger.

Carlqvist (1969, 1982a,c) finds that in a relativistic double layer the distribution of charges  $Zn_+(x)$  and  $n_-(x)$  can be divided into three regions: two density spikes near the electrodes and one intermediate region with almost constant charge density. In a later paper Carlqvist gives examples of possible galactic DL voltage differences of  $10^{14}$  V. This means that by a straightforward extrapolation of what we know from our cosmic neighborhood, we can derive acceleration mechanisms which bring us up in the energy region of Cosmic Radiation.

### III DOUBLE LAYERS AND FROZEN-IN MAGNETIC FIELD LINES

#### A. Frozen-in Field Lines - A Pseudo-Pedagogical Concept

In Cosmical Electrodynamics I tried to give a survey of a field in which I had been active for about two decades. In one of the chapters I treated magnetohydrodynamic waves. I pointed out that in an infinitely conductive magnetized fluid the magnetic field lines could be considered as "frozen" into the medium - under certain conditions - and this concept made it possible to treat the waves as oscillations of frozen-in strings.

The "frozen-in" picture of magnetic field lines differs from Maxwell's views. He defined a magnetic field line as a line which everywhere is parallel to the magnetic field. If the current system which produce the field changes, the magnetic field changes and field lines can merge or reconnect. However, if the current system is constant the magnetic field is also constant. To speak of magnetic field lines moving perpendicular to the field makes no sense. They are not material.

In a detailed analysis of the motion of magnetic lines of force Newcomb (1958) has demonstrated that "it is permissible to ascribe a velocity  $v$  to the line of force if and only if  $\nabla \times (E + v \times B)$  vanishes identically".

I thought that the frozen-in concept was very good from a pedagogical point of view, and indeed it became very popular. In reality, however, it was not a good pedagogical concept but a dangerous "pseudo-pedagogical concept". By "pseudo-pedagogical" I mean a concept which makes you believe that you understand a phenomenon whereas in reality you have drastically misunderstood it.

I never believed in it 100% myself. This is evident from the chapter on "magnetic storms and aurora" in the same monograph. I followed the Birkeland-Störmer general approach but in order

to make that applicable to the motion of low-energy particles in what is now called the magnetosphere it was necessary to introduce an approximate treatment (the "guiding-centre" method) of the motion of charged particles. (As I have pointed out in CP III.1, I still believe that this is a very good method for obtaining an approximate survey of many situations and that it is a pity that it is not more generally used.) The conductivity of a plasma in the magnetosphere was not relevant.

Some years later criticism by Cowling made me realize that there was a serious difficulty here. According to Spitzer's formula for conductivity, the conductivity in the magnetosphere was very high. Hence the frozen-in concept should be applicable and the magnetic field lines connecting the auroral zone with the equatorial zone should be frozen-in. At that time (-1950) we already knew enough to understand that a frozen-in treatment of the magnetosphere was absurd. But I did not understand why the frozen-in concept was not applicable. It gave me a headache for some years.

In 1963 Carl-Gunne Fälthammar and I published the second edition of Cosmical Electrodynamics together. He gave a much higher standard to the book and new results were introduced. One of them was that a non-isotropic plasma in a magnetic mirror field could produce a parallel electric field  $E_{\parallel}$ . We analyzed the consequences of this in some detail, and demonstrated with a number of examples that in the presence of an  $E_{\parallel}$  the frozen-in model broke down. On p. 191 we wrote:

"In low density plasmas the concept of frozen-in lines of force is questionable. The concept of frozen-in lines of force may be useful in solar physics where we have to do with high- and medium-density plasmas, but may be grossly misleading if applied to the magnetosphere of the earth. To plasma in interstellar space it should be applied with some care."

## B. Magnetic Merging - A Pseudo-Science

Since then I have stressed in a large number of papers the danger of using the frozen-in concept. For example, in a paper "Electric current structure of the magnetosphere" (Alfvén, 1975) I made a table showing the difference between the real plasma and "a fictitious medium" called "the pseudo-plasma", the latter having frozen-in magnetic field lines moving with the plasma. The most important criticism of the "merging" mechanism of energy transfer is due to Heikkila (1973) who with increasing strength has demonstrated that it is wrong. In spite of all this, we have witnessed at the same time an enormously voluminous formalism building up based on this obviously erroneous concept. Indeed, we have been burdened with a gigantic pseudo-science which penetrates large parts of cosmic plasma physics. The monograph CP treats the field-line reconnection (merging) concept in I.3, II.3 and II.5. We may conclude that anyone who uses the merging concepts states by implication that no double layers exist.

A new epoch in magnetospheric physics was inaugurated by L. Lyons and D. Williams' monograph (1985). They treat magnetospheric phenomena systematically by the particle approach and demonstrate that the fluid dynamic approach gives erroneous results. The error of the latter approach is of a basic character. Of course there can be no magnetic merging energy transfer.

I was naive enough to believe that such a pseudo-science would die by itself in the scientific community, and I concentrated my work on more pleasant problems. To my great surprise the opposite has occurred: the "merging" pseudo-science seems to be increasingly powerful. Magnetospheric physics and solar wind physics today are no doubt in a chaotic state, and a major reason for this is that part of the published papers are science and part pseudo-science, perhaps even with a majority for the latter group.

In those parts of solar physics which do not deal with the interior of the sun and the dense phosphere region (fields where the frozen-in concept may be valid) the state is even worse. It is difficult to find theoretical papers on the low density regions which are correct. The present state of plasma astrophysics seems to be almost completely isolated from the new concepts of plasma which the in situ measurements on space plasma have made necessary (see Section VII).

I sincerely hope that the increased interest in the study of double layers - which is fatal to this pseudo-science - will change the situation. Whenever we find a double layer (or any other  $E_{\parallel} \neq 0$ ) we hammer a nail into the coffin of the "merging" pseudo-science.

#### IV DOUBLE LAYER AS A MECHANISM FOR ENERGY RELEASE

##### A. Double Layer as a Circuit Element

It is a truism to state that a DL which releases a power  $P \approx I\Delta V$  is part of a circuit in which a current  $I$  flows. We shall investigate the properties of such a circuit by starting with a conventional simple circuit and step by step adopt it to cosmical conditions.

Fig. 3 depicts a simple circuit containing a double layer, which following Carlqvist is depicted by a D and L written together with the L pointing in the direction of the current. Besides the double layer DL the circuit contains an inductance in which is stored an energy ("circuit energy").

$$W_L = \frac{1}{2} LI^2 = \frac{1}{2\mu_0} \int B_I^2 d\tau \quad (\text{IV.1})$$

where  $B_I$  is the magnetic field produced by the current  $I$  and  $d\tau$  is a volume element.

If a magnetized plasma (field  $B_0$ ) moves with velocity  $v$  in relation to the circuit it produces an e.m.f. in the circuit

$$\epsilon = \int \mathbf{v} \times \mathbf{B}_0 \cdot d\mathbf{s} \quad (\text{IV.2})$$

where  $d\mathbf{s}$  is a line element in the direction of  $\mathbf{I}$ .

If  $\epsilon > 0$  we have a generator transferring plasma power  $\epsilon I$  into the circuit; if  $\epsilon < 0$  we have a motor transferring circuit energy into kinetic energy of the plasma. In Fig. 3 we have introduced a symbol  $\oplus$  with the arrow parallel to  $\mathbf{I}$  to represent a generator and a similar one, but with the arrow antiparallel to  $\mathbf{I}$ , to represent a motor. Finally, the circuit may contain a resistance  $R$  which dissipates power  $RI^2$  into heat, etc.

An electrotechnical circuit like Fig. 3 consists essentially of metal wires. Is it realistic to use this for cosmic plasma problems? Apparently not. There are no metal wires in space. Further, if we want to use the circuit in connection with cosmic problems, most or all the circuit elements are distributed over cosmic distances. There have been many detailed studies made concerning the relations between kinetic energy of a plasma and currents, which give a deeper understanding of these processes than our circuit approach.

However, our purpose is not to study the detailed problems but to get a general survey of energy transport in cosmical physics. Is the circuit approach useful as a first approximation to such problems? Maybe.

A map of a city is useful in spite of the fact that it does not describe all the houses. Or rather because it does not attempt to do so. For calculating the motion of charged particles the guiding centre method is often preferable to the Störmer method even if it does not give the exact position of a particle at a certain moment. Or rather because it does not.

In space charged particles move more easily parallel to  $\mathbf{B}$  than perpendicular, and parallel currents are often pinched to filaments. A wire is not too bad an approximation to a pinched fi-

lament. Moreover, the generators-motors as well as the double layer are often confined to relatively small volume.

Hence, with all these reservations in mind we are going to apply the simple circuit of Fig. 3 to a number of cosmical problems in Section VI.

However, the circuit representation could - and must - be developed in many respects. For example when a current flows in large regions the simple inductance  $L$  should be replaced by a transmission line. See Fig. 4.

We should also observe that a theory of certain phenomena need not necessarily be expressed in the traditional language of differential equations etc. It could also be expressed as an equivalent circuit. The pioneer in the field is Boström who (1974) summarized his theory of magnetic substorms in the circuit shown in Fig. 5. If this method is developed it is quite possible that it will be recognized as the best way to represent energy transfer in cosmic plasmas.

#### B. Properties of the Circuit

Every circuit which contains an inductance  $L$  is intrinsically explosive (cf. II.D). The inductive energy  $W_I = 1/2 LI^2$  can be tapped at any point of the circuit. If we try to interrupt the current  $I$  the inductance tends to supply its energy to the point of interruption, where the power  $P = I\Delta V$  is delivered ( $\Delta V$  = voltage over the point of interruption and  $I$  the current at this point) This means that most of the circuit energy may be released in a double layer and if large it cause an explosion of the DL. In a laboratory plasma (Fig. 4b) this occurs due to a region of "negative resistance" in the current-voltage characteristic of the double layer (Carpenter et al., 1984; Torvén et al., 1985). (If the inductance is distributed over a considerable region, there are transient phenomena during which  $I$  is not necessarily the same over the whole circuit.)



In electro-technical literature in general, the resistors and inductances in the circuit may often be non-linear and sometimes distributed over larger volumes. Similarly, the DL symbol may mean one double layer but also a multiple double layer. We should also allow this circuit element to represent other types of  $E_{\parallel}$ ; for example, mirror-produced fields. Hasegawa and Uberoi (1982) have shown that under certain conditions a hydromagnetic wave produces a magnetic field-aligned electric field, which also should be included as DL. This means that DL stands for any electric field parallel to the magnetic field.

### C. Local Versus Global Plasma Theories

Consider a long, homogeneously magnetized uniform plasma. It is confined laterally by tube walls or by a magnetic field. It carries no longitudinal current. Information/energy is transmitted in a time  $T$  from one end to the other by sound waves or hydromagnetic waves or by diffusion. Phenomena with a time constant  $\ll T$  can be treated by local theories (because one end does not know what happens in the other). The Chapman-Cowling theory may be valid. However, if a longitudinal current  $I$  flows through the plasma and returns through an outer wire (or circuit) the situation is different. Except for rapid transients the current must be the same in the whole tube and in the wire. If the current is modulated in one end this information is rapidly transferred to the other end and to the wire. The current may produce double layers which accelerate electrons (and ions) to kV, MV, GV, etc. It may pinch the plasma, producing filaments. These effects also produce coupling between the two ends of the plasma column and reduce the coupling to its local environment.

Electrons accelerated in a DL in the plasma column may travel very rapidly from one end of the plasma column to the other.

Hence, if there is a current through a plasma we must use global theories, taking account of all the regions through which

the current through the plasma column flows. Local theories are not valid (except in special cases).

A global theory must also be used to describe the influence of a DL on the motions in the plasma column.

In a one-dimensional model the voltage drop is  $\Delta V$  but in a two-dimensional cylindrical model it is a maximum  $\Delta V$  at the axis but decreases to zero at a certain outer limit. Hence we have

$$P = \alpha I \Delta V$$

with  $0 < \alpha < 1$ . It is also required that there are radial electric fields in the surrounding plasma. These together with the magnetic field produce drift motions in the plasma column (Carlqvist, 1979; Raadu, 1984).

The theoretical treatment of a current-carrying plasma must start with locating the whole region in which the current flows. It is convenient to draw the circuit and determine the resistances, the inductances, and the generators and DL's. These elements are usually distributed and non-linear, and the circuit theory may be rather complicated.

The return current need not flow through a wire. it could very well flow through another plasma column. An example of this is the auroral current system. As pointed out in VI.A the energy is transferred from the cloud C to DL not by high energy particles nor by waves (and of course not by magnetic reconnection!). It is a property of the circuit. A global theory is necessary which takes account not only of the plasma cloud near the equatorial plane but also of the ionosphere and double layers which may be found in the lower magnetosphere. Another still more striking example is given in VI.C.

## V. TRANSFER OF KNOWLEDGE BETWEEN DIFFERENT PLASMA REGIONS

In CP (Alfvén, 1981) it is pointed out that the basic properties of a plasma are likely to be the same in different regions of cosmic plasmas. This is represented by Fig. 6, called the Cosmic Triple Jump.

The linear dimensions of plasma vary by  $10^{27}$  in three jumps of  $10^9$

from laboratory plasmas	- 0.1 m
to magnetospheric plasmas	- $10^8$ m
to interstellar plasmas	- $10^{17}$ m
up to the Hubble distance	- $10^{26}$ m

Including laser fusion experiments brings us up to  $10^{32}$  orders of magnitude. New results in laboratory plasma physics and in situ measurements by spacecraft in the magnetospheres (including the heliosphere) make sophisticated plasma diagnosis possible out to the reach of spacecraft ( $\sim 10^{13}$  m). Plasmas at larger distances should to a large extent be investigated by extrapolation. This is possible because of our increased knowledge of how to translate results from one region to another.

Fig. 6 shows us an example of how cosmogony (formation of the solar system) can be studied by extrapolation from magnetospheric and laboratory results, supplemented by our knowledge about interstellar clouds. When better instruments for observing the plasma universe in X-rays and  $\gamma$ -rays are developed we may get more information from these than from visual observations. (See Alfvén, 1986b.)

Fig. 7 contains essentially the same information as Fig. 6. It demonstrates that plasma research has been based on highly idealized models, which did not give an acceptable model of the observed plasma. The necessary "paradigm transition" leads to theories based on experiments and observations. It started in the laboratory about 20 years ago. In situ measurements in the

magnetospheres caused a similar paradigm transition there. This can be depicted as a "knowledge expansion", which so far has stopped at the reach of spacecraft. The results of laboratory and magnetospheric research should be extrapolated further out. When this knowledge is combined with direct observations of interstellar and intergalactic plasma phenomena, we can predict that a new era in astrophysics is beginning, largely based on the plasma universe model.

## VI. EXAMPLES OF COSMIC DOUBLE LAYERS

In order to demonstrate the usefulness of the equivalent circuit methods we shall here apply it to a variety of different cosmical problems.

### A. Auroral Circuit

The auroral circuit is by far the best known. It is derived from a large number of measurements in the magnetosphere and in the ionosphere which were pioneered by the Applied Physics Laboratory at Johns Hopkins University.

Zmuda and Armstrong (1974) observed that the average magnetic field in the magnetosphere had superimposed on it transverse field which they interpreted as due to hydromagnetic waves. Inspired by discussions with Fälthammar, Dessler suggested that the transverse field components instead indicated electric currents essentially parallel to the magnetic field lines (Cummings and Dessler, 1967).

This means that it was Dessler who discovered the electric currents which Birkeland had predicted. Dessler called them "Birkeland currents", a term which is now generally accepted and sometimes generalized to mean all currents parallel to the magnetic fields. I think that it is such a great achievement by Dessler to have interpreted the magnetospheric data in what we

now know is the correct way that the currents should be called Birkeland-Dessler currents.

In the auroral current system the central body (Earth and Ionosphere) maintains a dipole field (Fig. 8).  $B_1$  and  $B_2$  are magnetic field lines from the body. C is a plasma cloud near the equatorial plane moving in the sunward direction (out of the figure) producing an electromotive force

$$\epsilon = \int_{C_2}^{C_1} (\vec{v} \times \vec{B}) \cdot d\vec{s}$$

which gives rise to a current in the circuit  $c_1, a_1, a_2, c_2$ . The circuit may contain a double layer DL with the voltage  $\Delta V_D$  which essentially is used for accelerating auroral electrons. The energy is transferred from C to DL not magnetic merging or field reconnection. It is a property of the electric circuit (and can also be described by the Poynting vector (see Fig. 8)).

### B. Heliospheric Current

In a way which is described in CP II.4.2, we go from the auroral circuit to the heliospheric circuit (Fig. 9).

The sun acts as a unipolar inductor (A) (cf. Fig. 4a) producing a current which during odd solar cycles goes outward along the axes in both directions and inward in the equatorial plane. The current closes at large distances ( $B_3$ ), but we do not know where. The equatorial current layer is often very inhomogeneous. Further, it moves up and down like the skirt of a ballerina. In even solar cycles the direction of the current is reversed.

By analogy with the magnetospheric circuit we may expect the heliospheric circuit to have double layers. They should be located at the axis of symmetry, but perhaps preferentially in those solar cycles when the axial current is directed away from

the sun.

No one has yet tried to predict how far from the sun they should be located. They should produce high energy electrons and synchrotron radiation from these should make them observable as radio sources. Further, they should produce noise. They may be observable from the ground, but so far no one has cared to look for such objects.

### C. Double Radio Sources

If in the heliospheric circuit we replace the rotating magnetized sun by a galaxy, which is also magnetized and rotating, we should expect a similar current system, but magnified by about 9 orders of magnitude (Fig. 10 and CP II.4). This seems to be a very large extrapolation, but in fact a number of successful extrapolations from the laboratory to the magnetosphere are by almost the same ratio. (Of course all theories of plasma phenomena in regions which cannot be investigated by in situ measurements are by definition speculative!)

The e.m.f. is given by Eq.(IV.2), taken from the galactic center out to a distance where the current leaves the galaxy, which may be the outer edge. Inside the galaxy the current may flow in the plane of symmetry similar to the current sheet in the equatorial plane of the sun, but whether the intergalactic picture is correct or not is not really important to our discussion here. The e.m.f. which derives from the galactic rotation is applied to two circuits in parallel, one to the "north" and one to the "south" (see Fig. 10). As galaxies often are highly north-south symmetric it is reasonable that the two circuits are similar. Hence we expect a high degree of symmetry in the current system (at least under idealized conditions).

In the magnetosphere, the current flowing out from the ionosphere produces double layers (or magnetic mirror induced

fields) at some distance from the earth. Because of the similarity of the plasma configuration, we may expect double layers at the axis of a galaxy, and a large release of energy in them. It has been suggested that the occurrence of such double layers is the basic phenomenon producing the double radio sources. For the details of this theory see CP.

In the galactic circuit, the e.m.f. is produced by the rotating magnetized galaxy acting as a homopolar inductor, which implies that the energy is drained from the galactic rotation, but from the interstellar medium, not from the stars. By the same mechanisms as in the auroral circuit, it is transferred first into circuit energy and then to the double layers where in each the power  $P = I\Delta V$  is released. In a single DL or a series of DL's on each side of the galaxy, an acceleration of charged particles takes place. From the magnetosphere we know that layers are produced when the current flows outwards. (Whether double layers can be formed when the current flows inwards is still an open question.) If the same is true in the galactic case, there is a flow of thermal electrons to the layer from the outside and when passing a series of double layers the electrons are accelerated to very high energies. Hence, a beam of very high energy electrons is emitted from the double layer along the axis towards the central galaxy. This process is the same as the one which produces auroral electrons, only scaled up enormously both in size and energy. In analogy with the current in the magnetotail, the current in the equatorial plane of a galaxy may also produce double layers, which may be associated with large releases of energy.

Fig. 10a shows a radio astronomy picture of a double radio source. The DL's produced by the current system (Fig. 10b) should be located at the outer edges of the strong radio source. When electrons conducting the currents outside the double layer reach the double layer, they are accelerated to very high energies. Similarly, ions reaching the double layer on their outward motion from the central galaxy will be accele-

rated outwards when passing the double layers. The strong axial current produces a magnetic field, which pinches the plasma, confining it to a cylinder close to the axis.

Although the electrons are primarily accelerated in the direction of the magnetic field, they will be scattered by magnetic inhomogeneities and spiral in such a way that they emit synchrotron radiation. The accelerated electrons will be more like an extremely hot gas than a beam. With increasing distance from the double layer the electrons will spread and their energy and hence their synchrotron emission will decrease. This is in agreement with observations. It is possible that some of them will reach the central galaxy and produce radio emission there. It is also possible that the observed radio emission from the central galaxy is due to some other effect produced by the current (there are several mechanisms possible). Such phenomena in the central galaxy will not be discussed here.

The ions passing the double layer in the outward direction will be accelerated to the same energy as the electrons. Because of their larger rest mass, they will not emit much synchrotron radiation.

It should be stressed again that, just as in the magnetosphere and in the laboratory, the energy released in the double layer derives from circuit energy and is transferred to it by electric currents which essentially consist of relatively low energy particles. There is no need for a beam of high energy particles (or plasmons) to be shot out from the central galaxy. On the contrary, the central galaxy may be bombarded by high energy electrons which have obtained their energy from the double layer.

An attempt to a semi-quantitative analysis of the double radio galaxies is given in CP. It is likely that modifications are needed.



#### D. Solar Prominence Circuit. Solar Flares

The circuit consists of a magnetic flux tube above the photosphere and part of photosphere (see Fig. 11). the generator is in the photosphere and is due to a whirl motion in sunspot magnetic field.

Generator output increases the circuit energy which can be dissipated in two different ways: 1. When current density surpasses critical value an exploding DL is produced in which most of the circuit energy is released. This causes a solar flare (Alfvén and Carlqvist, 1967; Carlqvist, 1969). Hénoux (1985) has recently given an interesting study of solar flares and concludes that a current disruption by DL's is an appealing explanation of solar flares. 2. Under certain circumstances the electromagnetic pressure of the current loop may produce a motor which gives rise to a rising prominence.

#### E. Magnetic Substorms

According to Boström (1974) and Akasofu (1977), an explosion of the transverse current in the magnetotail gives an attractive mechanism for the production of magnetic substorms (see Fig. 5). Boström has shown that an equivalent magnetic substorm circuit is a way of presenting the substorm model. The onset of a substorm is due to the formation of a double layer, which interrupts the cross-tail current so that it is redirected to the ionosphere.

#### F. Currents and Double Layers in Interstellar Space

As it is relatively easy to measure magnetic fields, it is natural that the first description of the electromagnetic state of interstellar and intergalactic space is based on a magnetic field description. However, as no one claims - at least not explicitly - that the magnetic fields are curl-free, we must have a network of currents. As investigations of DL's (and quite a

few other phenomena) require explicit pictures of electric currents, it is essential to apply these pictures (cf. Fig.2).

Filamentary structures were quite generally observed already long ago, and may be observed everywhere where sufficient accurate observations can be made. There are a number of processes by which they are generated. For example, the heliospheric current system must close at large distances (cf. Fig. 9) and it is possible - perhaps likely - that this is done by a network of filamentary currents. Many such filaments may produce DL's and some of these may explode.

#### G. Double Layers as a New Class of Celestial Objects

The general structure and evolution of such a network of currents, including their production of DL's, has not yet been investigated. It is possible that under certain circumstances the final destiny of a set of currents is DL's, perhaps exploding DL's. DL's may be considered as a new class of celestial objects. We have already given an example of this in the interpretation of double radio sources as DL's.

#### H. X-ray and $\gamma$ -ray Bursts

When a number of explosions are observed, such as  $\gamma$ -ray and X-ray bursts, one may try to explain them as exploding DL's.

However, another possible source of energy is annihilation (CP, VI.3). There is also a possibility that they may be due to double layers in a baryon symmetric universe.

#### I. Double Layers as a Source of Cosmic Radiation

As pointed out in II.E, relativistic DL's in interstellar space may accelerate ions up to cosmic ray energies (see Carlqvist (1986)).

## VII. DOUBLE LAYERS IN TEXTBOOKS

As has been pointed out many times (see e.g. CP I Alfvén, 1982) in situ measurements in the magnetospheres and progress in laboratory plasma physics have caused a "paradigm transition" which means that a number of old concepts have to be abandoned and a number of new phenomena must be taken into account. M. Azar (1986) has made a search through some of the most generally used textbooks in astrophysics, in which of these the new concepts have been presented to the students in astrophysics. His results are listed in Table I.

The table gives the surprising and depressing result that the students in astrophysics still are kept ignorant of what has happened in plasma physics.

Double layers were analyzed in detail by Langmuir (1929a). The development described in III.A demonstrated that there must be "double layers" in a generalized sense (= magnetic field aligned electric field) so the first decisive evidence for their existence in the magnetosphere dates from 1962. The real discovery of double layers in the magnetosphere is due to Gurnett (1972). But still there are only 2 out of 17 textbooks which even mention that anything like that could exist.

The use of "equivalent circuits" is discussed in Alfvén and Fälthammar (1963) and further in a number of papers. Boström (1974) has given the most interesting account of their use. Still, Akasofu is the only one in the list who has understood the value of this in cosmic physics.

That parallel currents attract each other was known already at the times of Ampere. It is easy to understand that in a plasma currents should have a tendency to collect to filaments. In 1934 it was explicitly stated by Bennett that this should lead to the formation of a pinch. The problem which led him to the discovery was that the magnetic storm producing medium (solar wind with present terminology) was not flowing out uniformly

from the sun. Hence it was a problem in cosmic physics which led to the introduction of the pinch effect.

Today everybody who works in fusion research is familiar with pinches. Indeed, several thermonuclear projects are based on pinches. Pinches in cosmical physical are discussed in detail in Alfvén and Fälthammar (1963), and futher in a large number of papers; see CP II,4, But to most astrophysicists it is an unknown phenomenon. Indeed, important fields of research, e.g., the treatment of the state in interstellar regions, including the formation of stars, are still based on a neglect of Bennett's discovery more than half a century ago. As shown in the table, present day students in astrophysics hear nothing about it. In a recent survey article in Science M.M. Waldrop (1985) described some "mysterious" threads which were claimed to be different from anything earlier discovered. Published photographs indicated that these phenomena are likely to be common filamentary structures; indeed, have been well-known since 1934 (Alfvén, 1986a).

In conclusion, it seems that astrophysics is too important to be left in the hands of theoretical astrophysicists who have got their education from the listed textbooks. The space data from astronomical telescopes should be treated by scientists who are familiar with laboratory and magnetospheric physics, circuit theory, and of course modern plasma physics. More than 99% of the universe consists of plasma, and the ratio between electromagnetic and gravitational forces is  $10^{39}$ .

## VIII. ROEDERER'S INTERDISCIPLINARIFICATION

### A. The Roederer Syndrome

In his article "Tearing Down Disciplinary Barriers" (EOS, Oct. 1, 1985, p. 681) Juan G. Roederer points out the conflict between the demand for "increased specialization on one hand and

the pursuit of an increasingly interdisciplinary approach on the other".

This is important. Indeed, in the present state of science specialization is favored to such an extent that science is split up into a number of increasingly small specialties. We lack the global view. This is evident from the preceding section.

We should remember that there once was a discipline which was called "Natural Philosophy" ("reine Naturwissenschaft"). Unfortunately this discipline seems not to exist today. It has been renamed "science" but science of today is in danger of losing much of the Natural Philosophy aspect.

Roederer further discusses the psychological and structural causes for the loss of the global view, and points out that one syndrome of causes is the "territorial dominance, greed, and fear of the unknown". Scientists tend to "resist interdisciplinary inquiries into their own territory... In many instances, such parochialism is founded on the fear that intrusion from other disciplines would compete unfairly for limited financial resources and thus diminish their own opportunities for research".

#### B. Microscale Example

All this agrees with my own experience. When running a lab I found that one of my most important activities was to go from room to room and discuss in depth the problems which a certain scientist or a group of scientists was trying to understand. It often happened that one group reported that in their field they had a special problem which they could not possibly understand. I told them that if they cared to open the door to the next room - it was not locked! - just this special problem had been solved half a year ago, and if they injected the solution into their own field, this would take a great leap forward. Often they were not at all happy for this suggestion, probably

because of the syndrome which Roederer has discussed, but when faced with "tearing down the disciplinary barriers" within the laboratory they realized how important such action is for progress (cf. II.D). This may be considered a mild case of the Roederer syndrome.

Such an example from the microscale structure of science supports Roederer's general views, but examples from the macroscale structure are much more important. Large parts of this lecture have been a series of examples of the malady which Roederer describes.

The lack of contact between Birkeland's and Langmuir's experimental-theoretical approach on the one hand and the Chapman-Cowling mathematical-theoretical approach on the other has delayed progress in cosmic plasma physics by perhaps half a century. The many new concepts which came with the space age begin to be understood by magnetospheric physicists but have not yet reached the textbooks in astrophysics, a delay of one or two decades, often more, as seen in the preceding section. Very few if any deny that (at least by volume) more than 99% of the universe consists of plasma but students in astrophysics are kept ignorant even of the existence of important plasma phenomena like those listed in Table I.

Dr Roederer's prescription for curing this serious disease is "tearing down disciplinary barriers", indeed "interdisciplinarification" of science. This seems to be wise. However, we must suspect that to many astrophysicists this is bitter medicine. Can we find ways to sweeten it?

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	DL	CV	PE	Circ.
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<u>Theoretical Astrophysics</u> Amsterdams, 1958 (New York: Pergamon Press)				
<u>Astrophysics: The Atmo- spheres of the Sun and Stars</u> L. M. Aller, 1963 (New York: The Macmillan Press)				
<u>Plasma Astrophysics</u> Kaplan and Tsvetovsk, 1973 (New York: Pergamon Press)				
<u>Astrophysics and Space Science</u> A. J. Mahan, 1965 (Englewood Cliffs, NJ: Prentice-Hall)				
<u>Plasma Astrophysics Vol. 2</u> D. B. Milrose, 1980 (New York: Gordon and Breach, Science Pub.)	X			
<u>Astrophysics and Stellar Astronomy</u> , T. L. Swihart 1968 (New York: John Wiley & Sons)				
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<u>Cosmic Electrodynamics</u> J. H. Piddington, 1964 (New York: John Wiley & Sons)				
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<u>Solar Flare Magnetohydrodynamics</u> E. R. Priest, 1982 (Dordrecht, Holland: D. Reidel Pub. Co.)				
<u>Physics of the Solar Corona</u> L. S. Muklovinskii, 1965 (New York: Pergamon Press)				
<u>Solar Terrestrial Physics</u> S. I. Akasofu and S. Chapman 1972 (London: Oxford University Press)	X			X
<u>Introduction to Space Science</u> Haynes, 1971 (New York: John Wiley & Sons)				
<u>Intro. to the Physics of Space</u> Roosel and Albert, 1970 (New York: McGraw-Hill Book Co.)				
<u>Physics of Magnetospheric Substorms</u> S. I. Akasofu, 1977 (Dordrecht, Holland: D. Reidel Publishing Co.)	X			X

X means that the field of research is at least mentioned. Blank squares mean that the student is kept ignorant of the fact that such a field exists.

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Table 1.



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FIGURE CAPTIONS

- Fig. 1 Plasma produced by an electric discharge. In case the plasma is inhomogeneous, either because its cross section varies or its chemical composition or its density varies, one or more double layers may be produced between the electrodes (cf. Torvén and Lindberg, 1980).
- Fig. 2 Dualism in plasma physics (cf. CP I.3).
- Fig. 3 Example of a simple electric circuit where the double layer symbol suggested by Carlqvist (1982) is used. The double layer is connected in series with a voltage source  $V$ , an inductance  $L$ , and a resistance,  $R$ . A current  $I$  flows in the circuit. The usual symbol for an e.m.f. (which is derived from a galvanic element) is replaced by the suggested symbol for a "generator". The arrow points in the direction of the current  $I$ . The same symbol with the arrow antiparallel to  $I$  represents a "motor" in which circuit energy is used to accelerate the plasma.
- Fig. 4a (Upper) In certain cases, e.g., if the circuit has large dimensions, the simple inductance  $L$  should be replaced by a transmission line. (Lower) A rotating magnetized celestial body often acts as a homopolar inductor.
- Fig. 4b Current-voltage characteristic of a laboratory double layer showing a region of negative resistance (Carpenter et al. 1984).
- Fig. 5 Boström (1974) has given a summary of his theory of magnetic substorms in the form of a circuit. Solar wind energy produces a cross-tail current in the neutral sheet. The arrow indicates that this current can give rise to a very large voltage. (In our terminology it

should be replaced by the DL symbol.) This causes the circuit energy to be discharged over the ionosphere, where it is observed as a magnetic substorm. At substorm onset, the resistance of the neutral sheet increases because a DL is produced and the tail current is redirected to the ionosphere.

Fig. 6 Cosmic Triple Jump.

The linear dimensions of plasma vary by  $10^{27}$  in three jumps of  $10^9$ :

from laboratory plasma	- 0.1 m
to magnetospheric plasmas	- $10^8$ m
to interstellar plasmas	- $10^{17}$ m
up to the Hubble distance	- $10^{26}$ m

including laser fusion experiments brings up to  $10^{32}$  orders of magnitude.

New results in laboratory plasma physics and from in situ measurements by spacecraft in the magnetospheres (including the heliosphere) make sophisticated plasma diagnosis possible out to the reach of spacecraft ( $\sim 10^{13}$  m). Plasma at larger distances should to a large extent be investigated by extrapolation. To some extent this is possible because of our increased knowledge of how to translate results from one region to another.

As an example, cosmogony (formation of the solar system) can be studied by extrapolation from magnetospheric and laboratory results, supplemented by our knowledge about interstellar clouds.

Fig. 7 Plasma research has been based on highly idealized models, which did not give an acceptable model of the observed plasma. The necessary "paradigm transition" leads to theories based on experiments and observations. It started in the laboratory about 20 years ago. In situ measurements in the magnetospheres caused a similar paradigm transition there.

This can be depicted as a "knowledge expansion", which unfortunately seems to have stopped at the reach of spacecraft. The results of laboratory and magnetospheric research should be extrapolated further out. When this knowledge is combined with direct observations of interstellar and intergalactic plasma phenomena, we can predict that a new era in astrophysics is beginning, largely based on the plasma universe model.

Fig. 8 Auroral circuit (seen from the sun) (cf. CP, Fig. II:17). The central body (earth and ionosphere) maintains a dipole field.  $B_1$  and  $B_2$  are magnetic field lines from the body.  $C$  is a plasma cloud near the equatorial plane moving in the sunward direction (out of the figure) producing a generator with

$$V = \int_{c_2}^{c_1} (\vec{v} \times \vec{B}) \cdot d\vec{s}$$

which gives rise to a current in the circuit on  $c_1$ ,  $a_1$ ,  $a_2$ ,  $c_2$  and  $c_1$ . In a double layer DL with the voltage  $\Delta V$ , the current releases energy at the rate  $P \approx I\Delta V$ , which essentially is used for accelerating auroral electrons. The energy is transferred from  $C$  to DL not by high energy  $\gamma$  particles or waves, and not by magnetic merging or field reconnection. It is a property of the electric circuit (and can also be described by the Poynting vector).

Fig. 9 Heliospheric circuit. The sun acts as a unipolar inductor (A) producing a current which goes outward along both the axes and inward in the equatorial plane and along the magnetic field lines  $B_1$ . The current must close at large distance ( $B_3$ ), either as a homogeneous current layer, or - more likely - as a pinched current.

Analogous to the auroral circuit, there may be double layers which should be located symmetrically at the sun's axes. Such double layers have not yet been discovered.

Fig. 10 Galactic circuit.

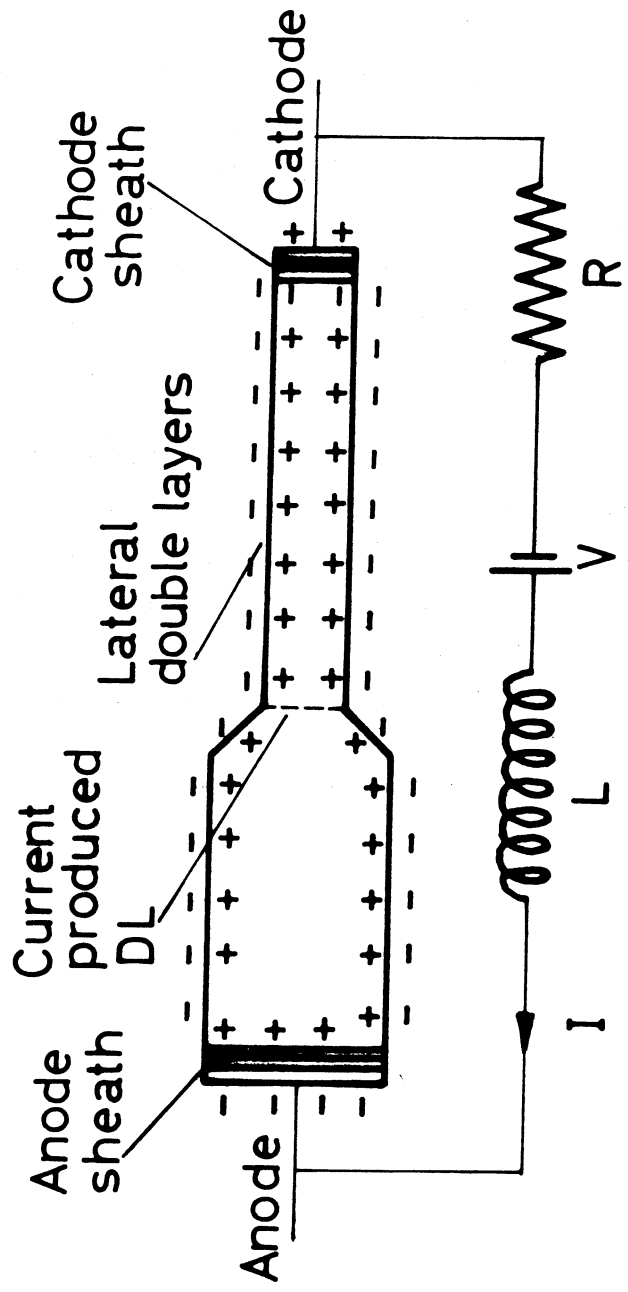
(a) Observed radio emission of Cygnus A (by Hargrave and Ryle 1974).

(b) the heliospheric circuit is scaled up by a factor  $10^9$  and the sun replaced by a galaxy located almost exactly between the radio sources (cf. CP, III.4.4). The radio emission is attributed to synchrotron emission by electrons accelerated in the double layers.

Fig. 11 Prominence-Solar Flare Circuit.

Whirling motions in the photosphere act as a generator, feeding energy into the circuit (which is similar to Fig. 3). The circuit energy can be released either as a solar flare produced by an exploding double layer and/or as kinetic energy in a rising prominence.

Fig.1





## TRANSLATION FORMULA

$$\nabla \times \vec{B} = \mu_0 \vec{i}$$

### MAGNETIC FIELD DESCRIPTION

#### MAGNETIC FIELDS ARE:

- Measured rather easily
- Basic for plasma anisotropy including high energy particle motion
- Gives a good description of some waves in plasmas

### ELECTRIC CURRENT DESCRIPTION

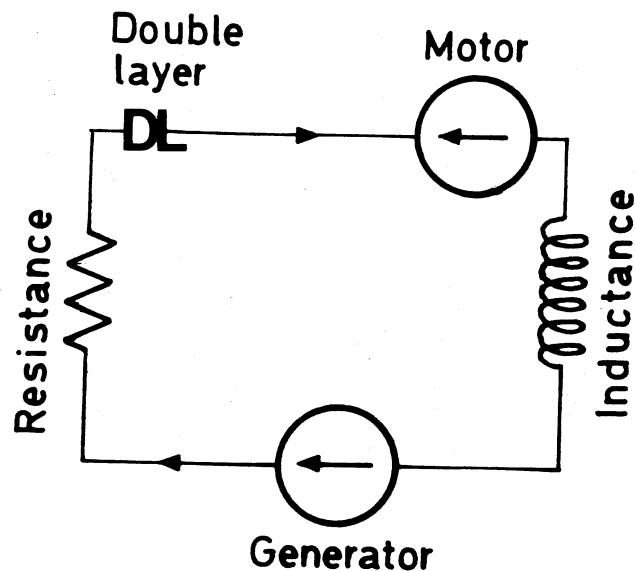
ELECTRIC CURRENTS ARE DIFFICULT TO MEASURE DIRECTLY BUT ESSENTIAL FOR UNDERSTANDING:

- Double layers
- Transfer of energy from one region to another
- Current sheet discontinuities
- Cellular structure of space
- Magnetic substorms, solar flares

The plasma dualism is somewhat analogous to the general particle field dualism in physics. The current description requires a new formalism with double layer and electric circuits as important ingredients.

Fig. 2

## SIMPLE CIRCUIT



Circuit energy  $W_C = LI^2/2$

Generator voltage  $V_G = \int_{\text{GEN}} \vec{v} \times \vec{B}_0 \cdot d\vec{s} > 0$

Motor voltage  $V_M = \int_{\text{MOT}} \vec{v} \times \vec{B}_0 \cdot d\vec{s} < 0$

Generator power  $P_G = IV_G$

Motor power  $P_M = IV_M$

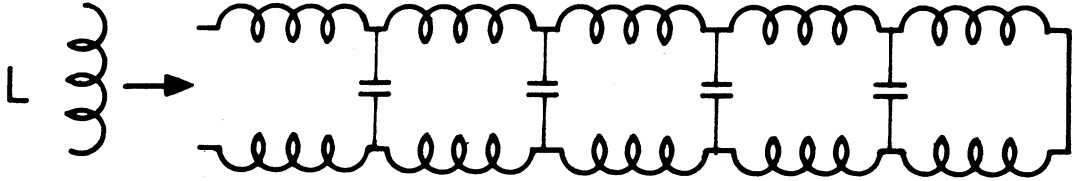
Double layer voltage  $\Delta V$

Power delivered to particles by DL  $P_X \approx I\Delta V$

Power losses in resistances etc.  $P_R = RI^2$

# OTHER SYMBOLS

If inductance is distributed L should be replaced by transmission line



Magnetized celestial body acting as homopolar inductor

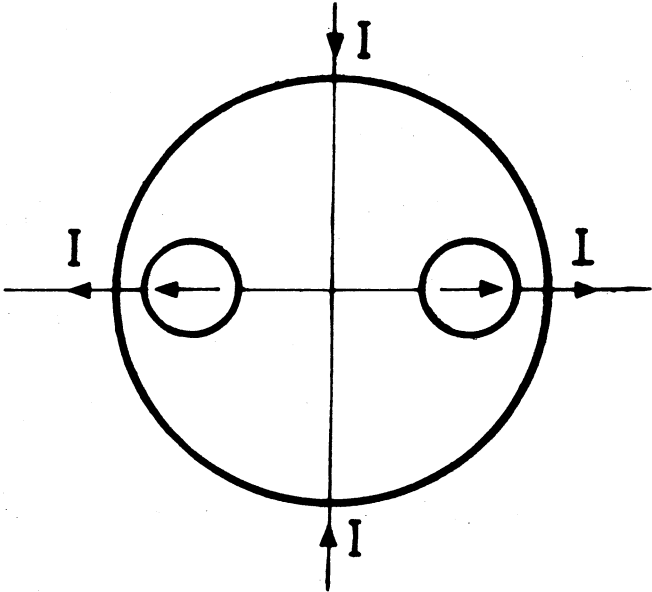


Fig. 4b

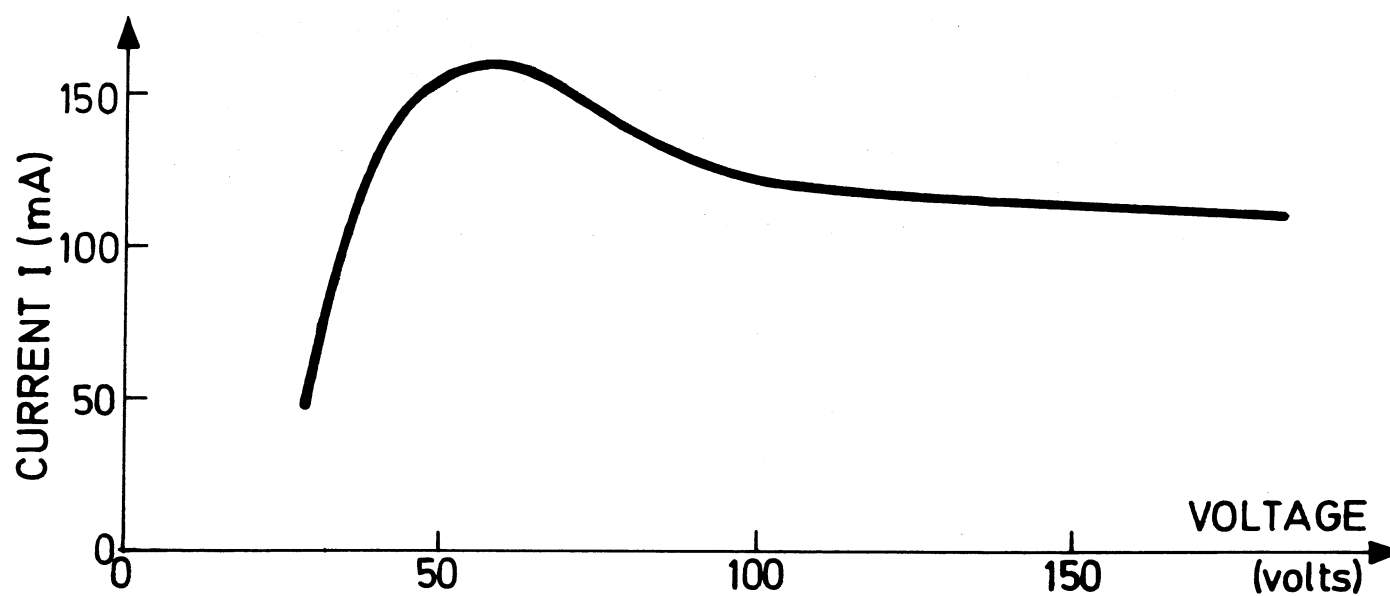
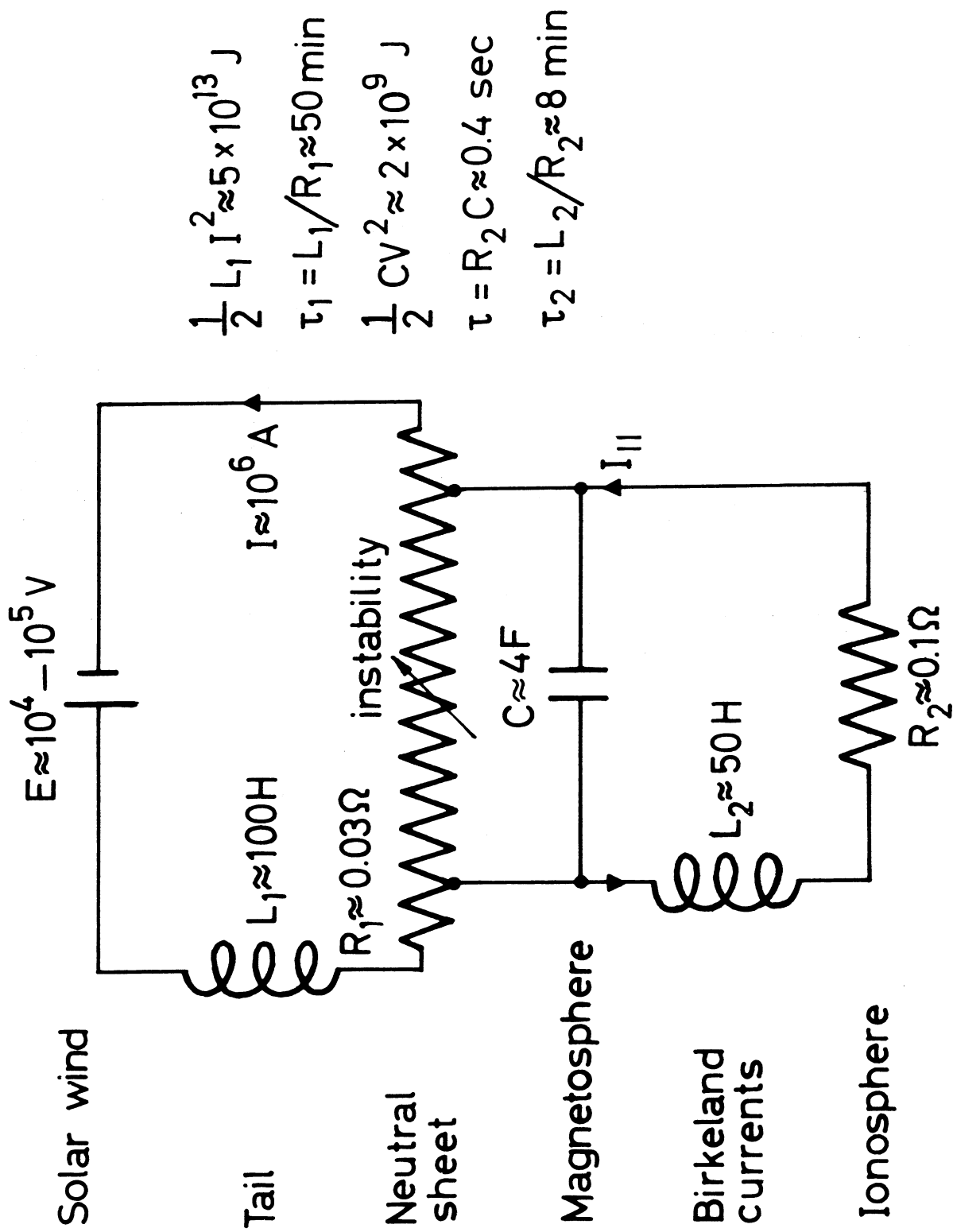


Fig. 5



$$\frac{1}{2} L_1 I^2 \approx 5 \times 10^{13} \text{ J}$$

$$\tau_1 = L_1 / R_1 \approx 50 \text{ min}$$

$$\frac{1}{2} C V^2 \approx 2 \times 10^9 \text{ J}$$

$$\tau = R_2 C \approx 0.4 \text{ sec}$$

$$\tau_2 = L_2 / R_2 \approx 8 \text{ min}$$

Fig.6

# TRANSFER OF KNOWLEDGE BETWEEN DIFFERENT PLASMA REGION

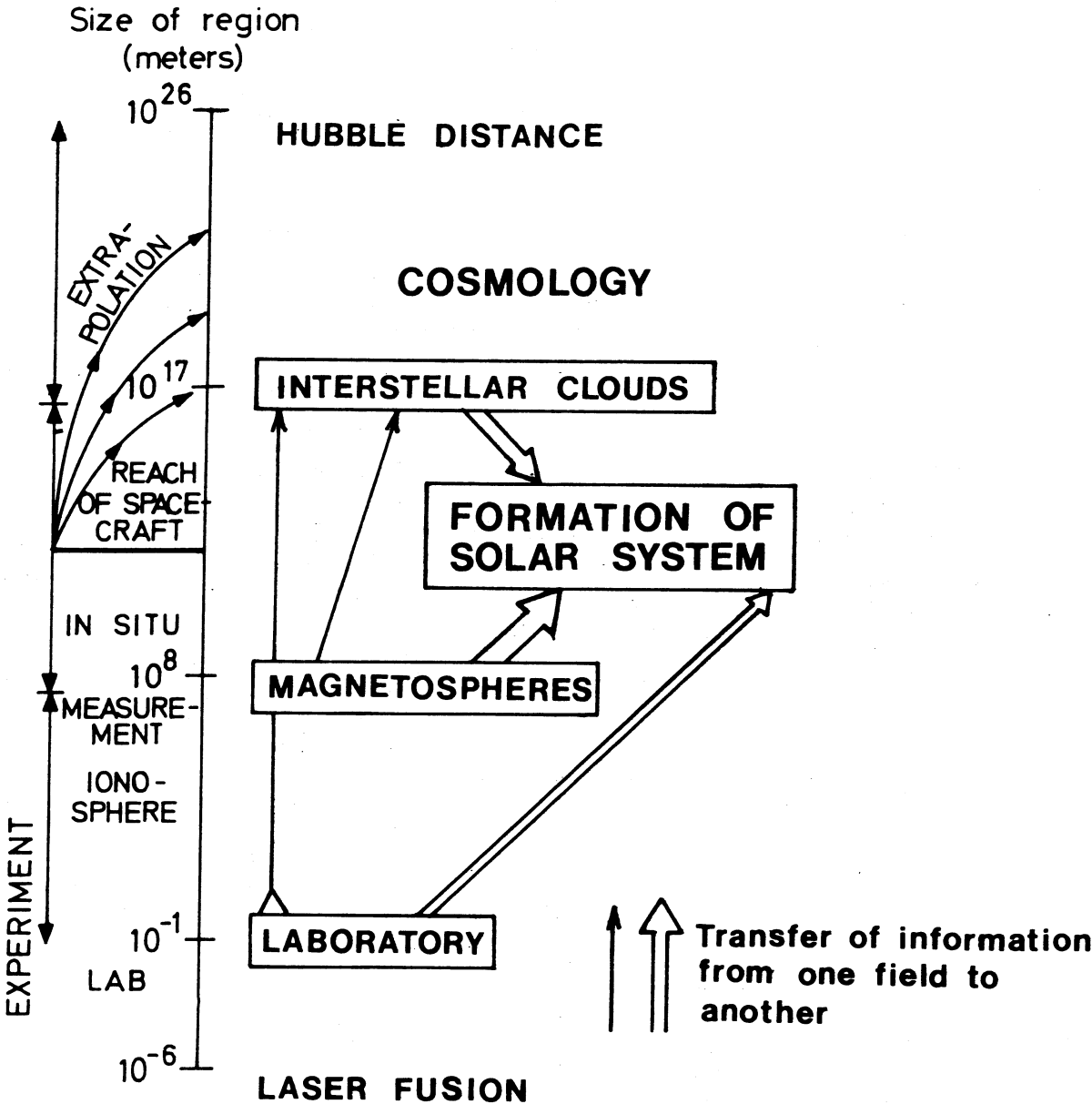




Fig.8

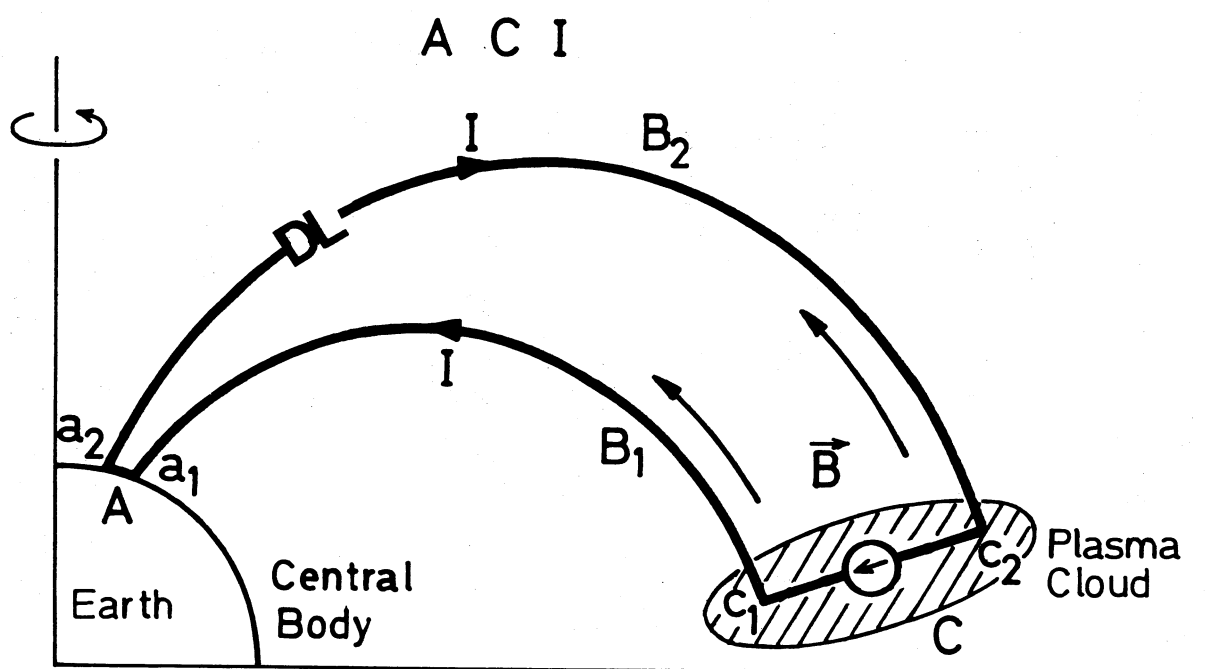




Fig.9

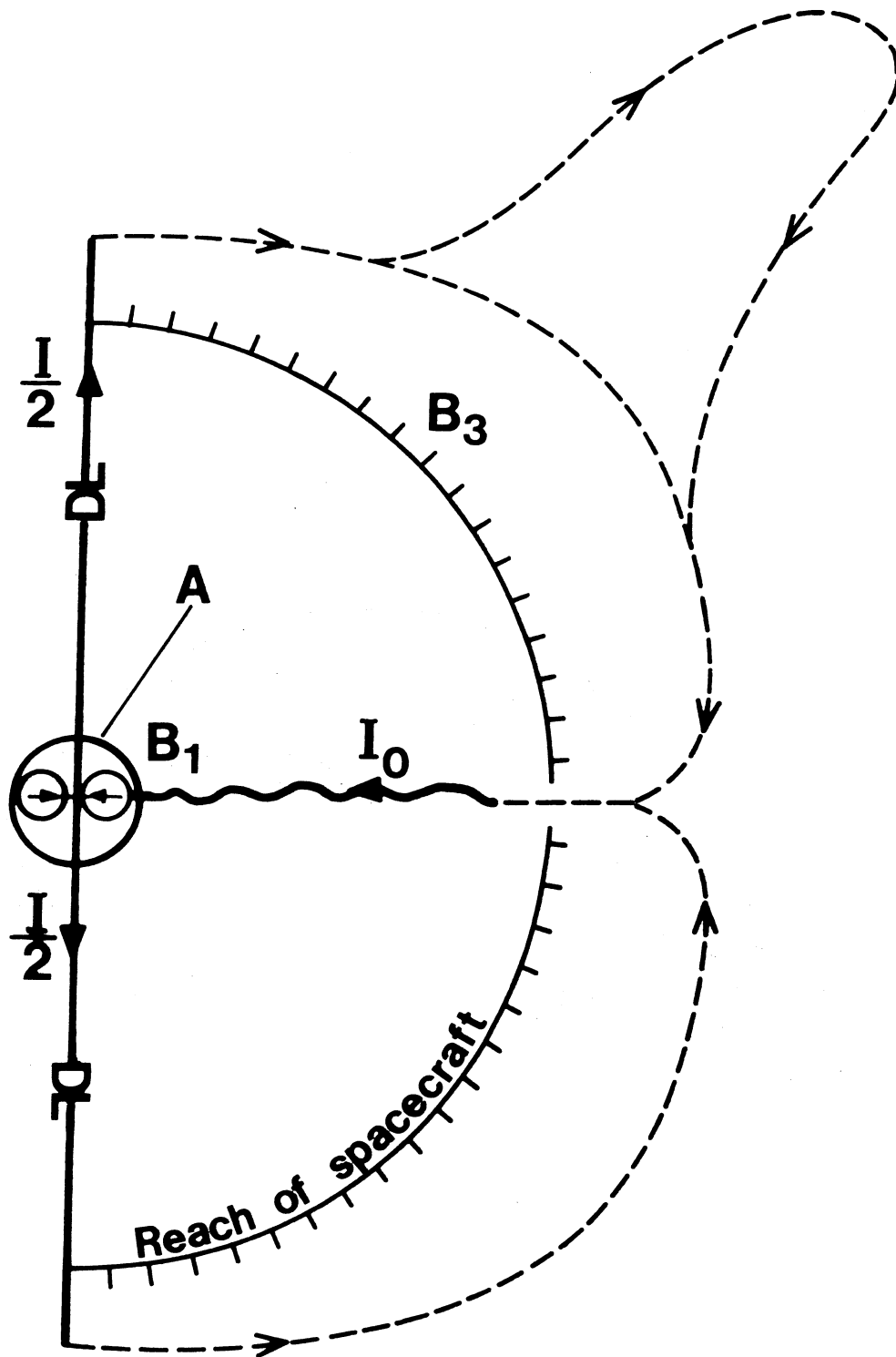


Fig. 10

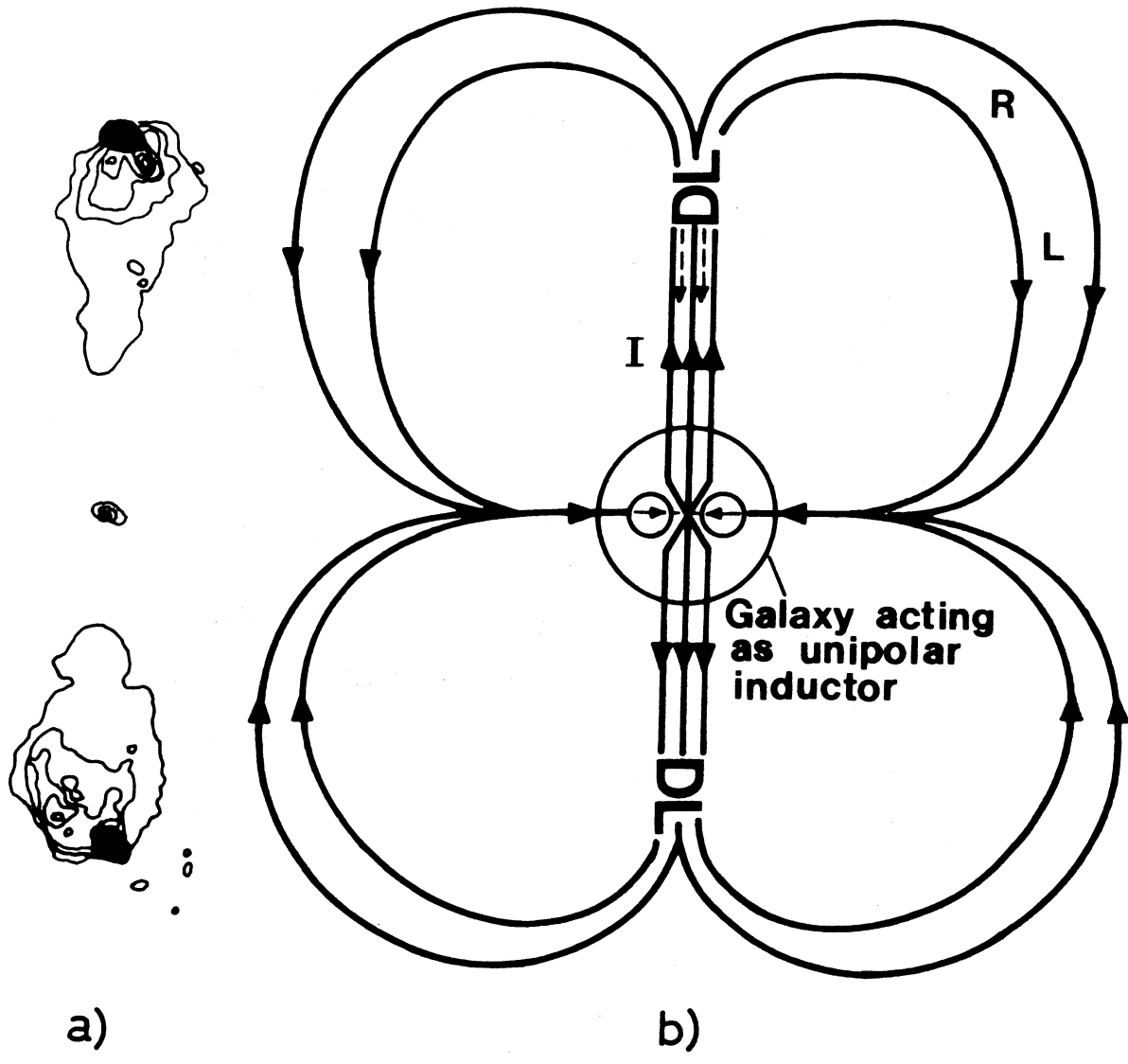
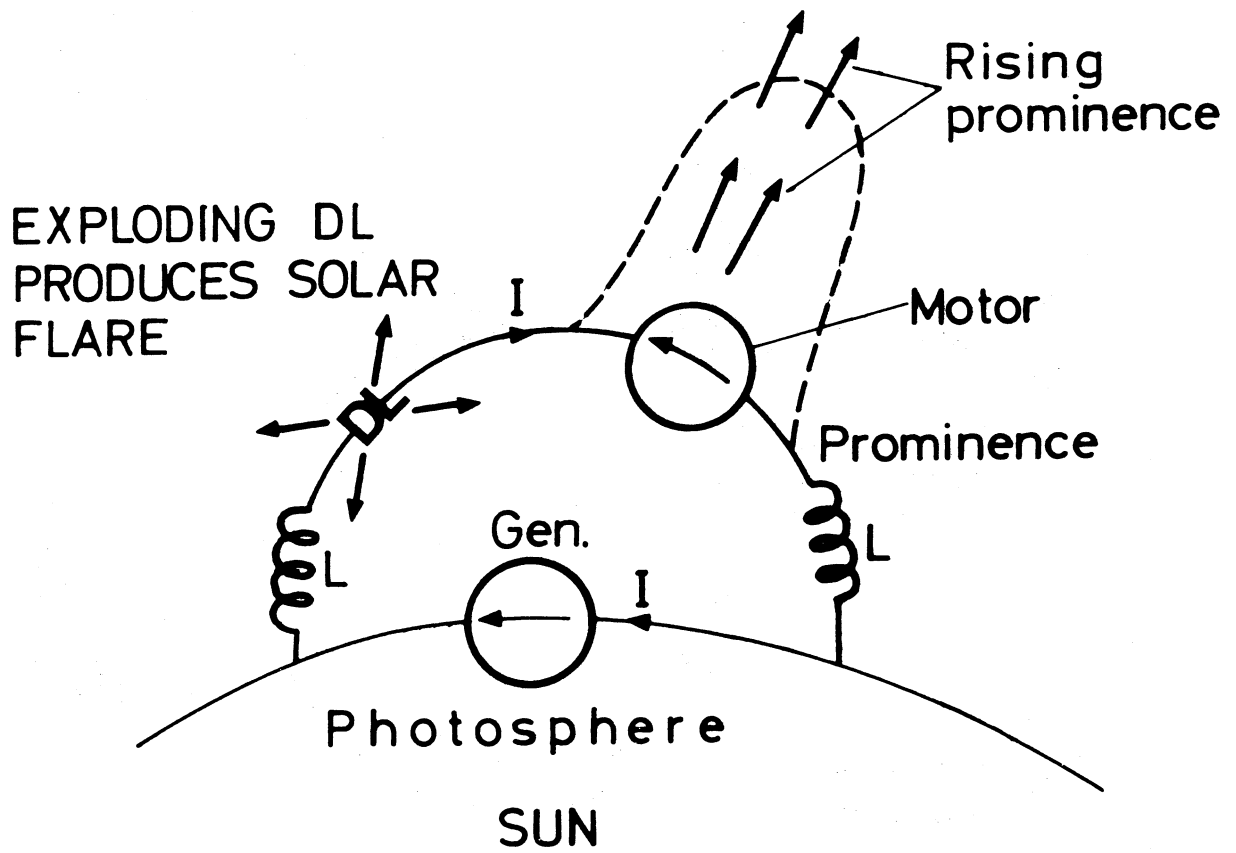


Fig. 11



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DOUBLE LAYERS AND CIRCUITS IN ASTROPHYSICS

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Abstract

As the rate of energy release in a double layer with voltage  $\Delta V$  is  $P \approx I\Delta V$ , a double layer must be treated as a part of a circuit which delivers the current  $I$ . As neither double layer nor circuit can be derived from magnetofluid models of a plasma, such models are useless for treating energy transfer by means of double layers. They must be replaced by particle models and circuit theory.

A simple circuit is suggested which is applied to the energizing of auroral particles, to solar flares, and to intergalactic double radio sources. Application to the heliospheric current systems leads to the prediction of two double layers on the sun's axis which may give radiations detectable from earth.

Double layers in space should be classified as a new type of celestial object (one example is the double radio sources). It is tentatively suggested in X-ray and  $\gamma$ -ray bursts may be due to exploding double layers (although annihilation is an alternative energy source).

A study of how a number of the most used textbooks in astrophysics treat important concepts like double layers, critical velocity, pinch effects and circuits is made. It is found that students using these textbooks remain essentially ignorant of

even the existence of these, in spite of the fact that some of them have been well known for half a century (e.g., double layers, Langmuir, 1929: pinch effect, Bennet, 1934). The conclusion is that astrophysics is too important to be left in the hands of the astrophysicist. Earth bound and space telescope data must be treated by scientists who are familiar with laboratory and magnetospheric physics and circuit theory, and of course with modern plasma theory. At least by volume the universe consists to more than 99% of plasma, and electromagnetic forces are  $10^{39}$  time stronger than gravitation.

Key words: Plasmas, Currents in plasmas, Double layers as circuit elements, Exploding double layers, Relativistic double layers, Cosmic radiation, X-ray,  $\gamma$ -ray bursts, Pinch effect, Local versus global theories, Magnetospheric-Heliospheric galactic currents.