Electric Currents in Cosmic Plasmas

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Since the beginning of the century, physics has been dualistic in the sense that some phenomena are described by a field concept and others by a particle concept. This dualism is essential also in the physics of cosmic plasmas: some phenomena should be described by a magnetic field formalism, and others by an electric current formalism. During the first period of evolution of cosmic plasma physics the magnetic field aspect has dominated, and a fairly exhaustive description has been given of those phenomena, like the propagation of waves, which can be described in this way. We have now entered a second period, which is dominated by a systematic exploration of the particle (or current) aspect. A survey is given of a number of phenomena which can be understood only from the particle aspect. These include the formation of electric double layers, the origin of 'explosive' events like magnetic substorms and solar flares, and further, the transfer of energy from one region to another. A useful method of exploring many of these phenomena is to draw the electric circuit in which the current flows and to study its properties. A number of simple circuits are analyzed in this way.

CONTENTS

1. CURRENTS AND MAGNETIC FIELDS

a. *Dualism in Physics*

Since the beginning of the century, physics has been dualistic in the sense that some phenomena are described by a field formalism, whereas others are treated in terms of particles. In the cosmic application of physics we have frequent examples of this dualism: the propagation of waves is treated by Maxwell's equations, but the charge of a grain in space is derived by considering the photons and electrons which hit it. There are also phenomena, like the Doppler effect, which can be treated from both the wave and the particle aspect.

This is all very well understood, but it is not so well recognized how deeply this dualism penetrates also into the field of cosmic plasmas. From Maxwell's first equation, which in a plasma can be written as

$$\text{curl}\,\mathbf{B} = (4\pi/c)\mathbf{i} \qquad (1)$$

we learn that we can describe electromagnetic phenomena in space either in terms of a magnetic field B or in terms of electric currents i. As magnetic fields are easy to measure and moreover the mathematical treatment becomes simpler if i is eliminated, it seems obvious that we should use the field description and eliminate i. For example, when we treat waves proceeding through a plasma, these are certainly associated with electric currents, but we can regard a current implicitly as a curl of the magnetic field and forget it explicitly.

However, when we do so, we lose the particle aspect of the current; i.e., we neglect the fact that an electric current in space consists in a motion of charged particles which have a certain mass, charge, and velocity and which are constituents of a gas with a certain temperature. Some of these properties can formally be introduced into the field description as bulk constants like ϵ, μ, and σ, but this gives a poor and often misleading representation of the particle phenomena.

In contrast to this approach the study of electric discharges, which starting a hundred years ago has clarified some essential properties of a plasma, approaches the phenomena from the particle aspect (motion of electrons and ions, formation of electrostatic double layers, establishment of non-Maxwellian velocity distribution, etc.). It is now obvious that several of the phenomena related to the particle aspect are of decisive importance also in cosmic plasmas and that by neglecting the particle aspect we deprive ourselves of the possibility of understanding some of the most important phenomena in cosmic plasma physics.

In the following we shall classify the plasma phenomena in magnetic field related phenomena and particle related or electric current related phenomena. The former early received much attention, but the latter have only recently been brought into the focus of interest.

b. *Particle Related Phenomena in Plasma Physics*

From the particle aspect we can derive the equation of motion of a test particle by calculating the sum of all forces from other particles. In principle, we need not speak about fields at all. However, it is convenient to introduce the electric field E' by the equation

$$\mathbf{F} = \sum \mathbf{f} = e\mathbf{E}' \qquad (2)$$

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Paper number 70194.

where **F** is the sum of all forces **f** acting on a test particle with charge e (neglecting gravitation).

The motion cf a charged particle can be completely described as being caused by the electric field E'. A magnetic field exerts a negligible force on the particle. However, if we make a relativistic transformation

$$\mathbf{E} = \mathbf{E}' - (1/c)\mathbf{v} \times \mathbf{B} \quad (3)$$

from the coordinate system which moves with the particle velocity **v** in relation to a coordinate system at rest, we have in this coordinate system another electric field **E**. It is convenient to use a coordinate system at rest and describe the motion of the particle by the velocity **v**. In this coordinate system the force acting on the charged particle is

$$\mathbf{f} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (4)$$

and **B** is given by (1).

Hence as seen from the coordinate system of the particle, B is unimportant, but it is convenient to introduce this concept in order to make the calculation of E' in (2) easier.

c. *Magnetic Field Lines*

A magnetic field line is by definition a line which everywhere is parallel to the magnetic field. If the current system changes, the shape of the magnetic field line changes, but it is not meaningful to speak about a translational movement of magnetic field lines.

The concept of 'frozen-in' magnetic field lines has played a certain role in plasma physics. However, the application of this concept requires

$$E_{\parallel} = 0 \quad (5)$$

In order to satisfy this the electric conductivity $\sigma_{\parallel}$ parallel to the magnetic field must be infinite. If we use the classical formula

$$\sigma_{\parallel} = \gamma(e^2 n_e \lambda_e / m_e v_e) \quad (6)$$

we find that under cosmic conditions, $\sigma_{\parallel}$ is usually so large that we can regard it as infinite (e and m_e are the electronic charge and mass, n_e is the number density of electrons, λ_e and v_e are the mean free path and the thermal velocity, and γ is a constant of the order of unity).

However, this is not enough because there are a number of phenomena which make (6) not applicable. Basically, these derive from the particle aspect of electric currents.

1. Formula (6) is derived under the condition that the mean free path λ_e of electrons is small in comparison with the characteristic length of variation of B, E, etc. This is often not satisfied in space plasmas. For example, in the outer magnetosphere and interplanetary space this condition is not valid.

2. When the current density becomes large enough, electrons may lose energy by a coupling between their motion and, for example, sound waves in the plasma (anomalous resistivity) [*Sagdeev*, 1975].

3. If the velocity distribution in a plasma is non-Maxwellian, a magnetic field gradient may produce an electric field $E_{\parallel} \neq 0$.

4. An electric current often produces electrostatic double layers (also called sheaths) associated with a discontinuous jump ΔV in the voltage.

As the effects mentioned above are common in low-density cosmic plasmas (especially in 'collisionless plasmas'), the frozen-in concept is very often invalidated. The concept has led to a serious misunderstanding of important phenomena, particularly when it has been combined with the 'magnetic field line reconnection' concept ('magnetic merging').

In order to demonstrate how unnecessary and misleading these concepts are we shall treat the simple case of the plasma flow in the magnetosphere assuming a stationary state [*Alfvén*, 1976]. We shall also use this example as an illustration of the relations between a magnetic field description and a particle description.

d. *Model of the Stationary Magnetosphere*

The stationary conditions of the magnetosphere are usually depicted by drawing the magnetic field lines (Figure 1). By the help of (1) we translate this into a current and particle picture. We place a current-carrying coil in the earth's interior which, if suitably designed, gives the earth's magnetic field. If we are satisfied with the axisymmetric dipole component, the coil may consist of a very small circular loop at the center of the earth.

Similarly, we let the interplanetary magnetic field be produced by a current in a very large coil. In the simplified case of

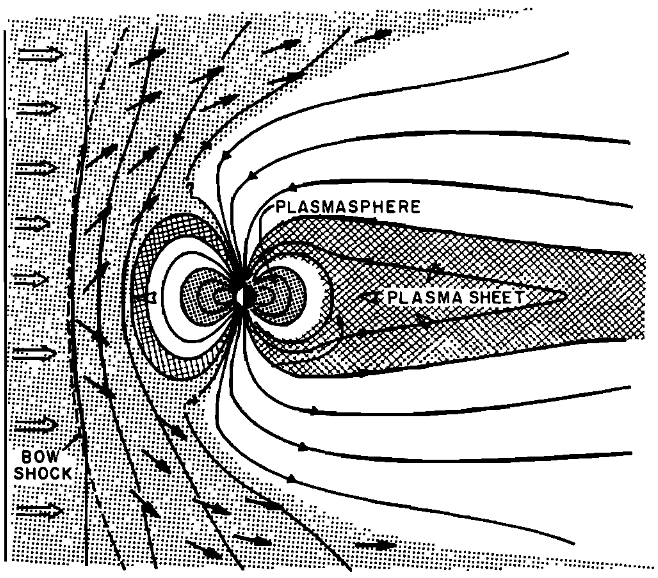

Fig. 1*a*. Conventional magnetic field of line picture of magnetosphere [after *Wolf*, 1975].

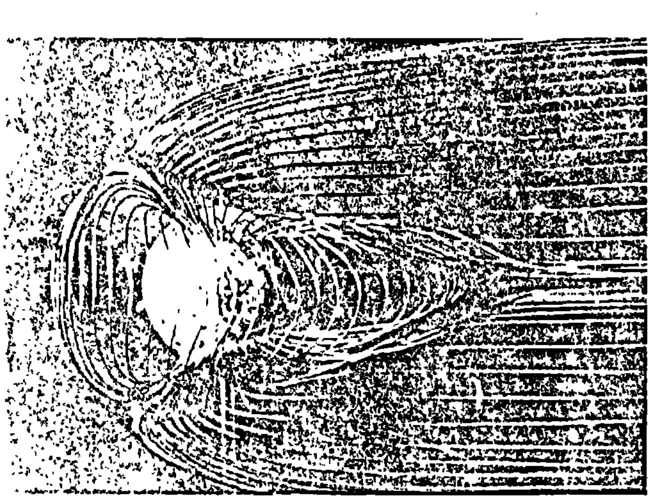

Fig. 1*b*. Wire model of magnetosphere field line constructed from terrelle experiment measurements (from Podgorny, personal communication, 1976).

a southward interplanetary field the coil may be a Helmholtz coil with its axis coinciding with the earth's axis.

To these we must further add a number of coils representing the secondary magnetic fields. In a simplified model [*Alfvén*, 1975] these consist of a double coil producing the magnetopause current system, a double coil producing the tail current system, and a system of coils producing the ionosphere-magnetosphere current system (Figure 2). By making the coil wires of very thin electrically insulated metal we can obtain a good approximation to the current system which in reality consists of distributed currents.

Similarly, we produce the electrostatic field by a number of electrostatic charges placed in suitable fixed positions. For example, in the simple case v = const, B = const, the interplanetary electric field which as seen from an earth-centered system is $\mathbf{E} = -(1/c)\mathbf{v} \times \mathbf{B}$ can be produced by two condenser plates separated by a large distance d and charged to a potential $V = dE$. Electric fields caused by space charge should be represented by a number of other electric charges.

In the stationary state that we consider, both the electric and the magnetic fields are static. We can depict the magnetic field by drawing the magnetic field lines (Figure 1), but it should be observed that a magnetic field line has the Maxwellian meaning. It is a line which everywhere has the direction of the magnetic field. To ask whether a field line 'moves' or not has no meaning. In our static vacuum model it is natural to depict field lines as immovable in relation to the coils which produce them, which means in relation to the earth.

e. Particle Motion in the Magnetosphere

So far our model contains no movable charged particles (outside the wires). In this vacuum model we inject one charged test particle either from interplanetary space or from the ionosphere. Its motion is completely determined by the electric and magnetic fields. As the magnetic field is static, the energy W of the particle is given by

$$W = W_0 + e \int \mathbf{E} \cdot d\mathbf{s} \qquad (7)$$

where W_0 is the initial energy, $d\mathbf{s}$ the line element, $\mathbf{E}$ the (static) electric field from the fixed charges, and e the charge of the particle.

Next, we inject a large number of solar wind particles (and particles from the ionosphere), still only a negligible fraction ϵ of what corresponds to the real case. When we assume that the mutual collisions (as well as the collisions with the model structure) are negligible, they will behave as a number of test particles. If our model is designed correctly, they will increase the space charge given by the fixed charges of the model by the fraction ϵ, and their flow close to the coil wires will increase the magnetic field by the same fraction. If we reduce all coil currents and all fixed charges by the fraction ϵ, we will return to the same electric and magnetic field as before the injection.

We now slowly increase ϵ to unity. At the same time we reduce the coil currents and the fixed charges so that eventually they become zero. It is easily seen that this can be done in such a way that during the whole process the electric and magnetic fields remain constant. We can now remove the model structure, and every particle will still move and change its energy as if it were a single test particle in the vacuum model. Our model now depicts how the plasma in our surroundings flows and changes its energy.

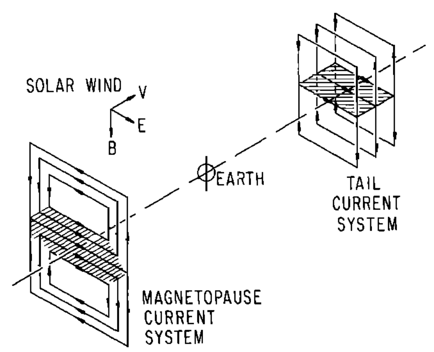

Fig. 2. Simplified current system giving the magnetic field of Figure 1.

f. Conclusions About the Stationary Model

Our gedankenexperiment shows that neither the injection of one test particle (or a small number of test particles) nor the full amount of solar wind particles calls for a change in the Maxwellian concept of magnetic field lines. There is no need for frozen-in field lines moving with the plasma and still less for field line reconnection or magnetic merging. The magnetic field remains static the whole time, and not a single field line is disconnected or reconnected. The energy of a charged particle is given by (7). There is no field line reconnection that can transfer energy to the particles nor release energy in any other way (see appendix).

If the magnetic field varies with time, the geometry near neutral points may change in such a way that field lines may be considered to disconnect and reconnect. It may be argued that in this case the usual field line reconnection formalism should be applicable. As will be shown in section 1*j*, this is not correct. The field line reconnection theories are also erroneous in this case.

g. Field Aspect and Current Aspect of Magnetized Cosmic Plasmas

The theoretical study of cosmic plasmas has so far largely been based on a field description. This has been very successful in accounting for those phenomena which are accessible by this approach. The study of waves in plasmas has especially given results of permanent value.

However, as we have stated in section 1*a*, there are a number of important phenomena which are not accessible by this approach. In fact, by eliminating the electric current, as is done in the magnetic field approach, we also eliminate the possibility of understanding a number of phenomena which are produced by electric currents. Examples of such phenomena are formation of electrostatic double layers and anomalous resistance effects; the release of energy in double layers, for example, in auroral double layers and in other parts of the magnetosphere; the transfer of energy from the solar wind to the magnetosphere; and 'explosive' events like magnetic substorms and solar flares.

It is just as impossible to understand these phenomena by a magnetic field formalism as it is to understand the photoelectric effect from Maxwell's equations alone.

Hence it is necessary to revise cosmic plasma physics in order to see it also from the particle or current aspect. Such an analysis must be based on what we know about the ionosphere, magnetosphere, and interplanetary space because these are the only regions which are accessible to in situ measurements, which means that we can confront theories with detailed observational facts. Astrophysics today runs the risk of being much too speculative. The only remedy of this is to base

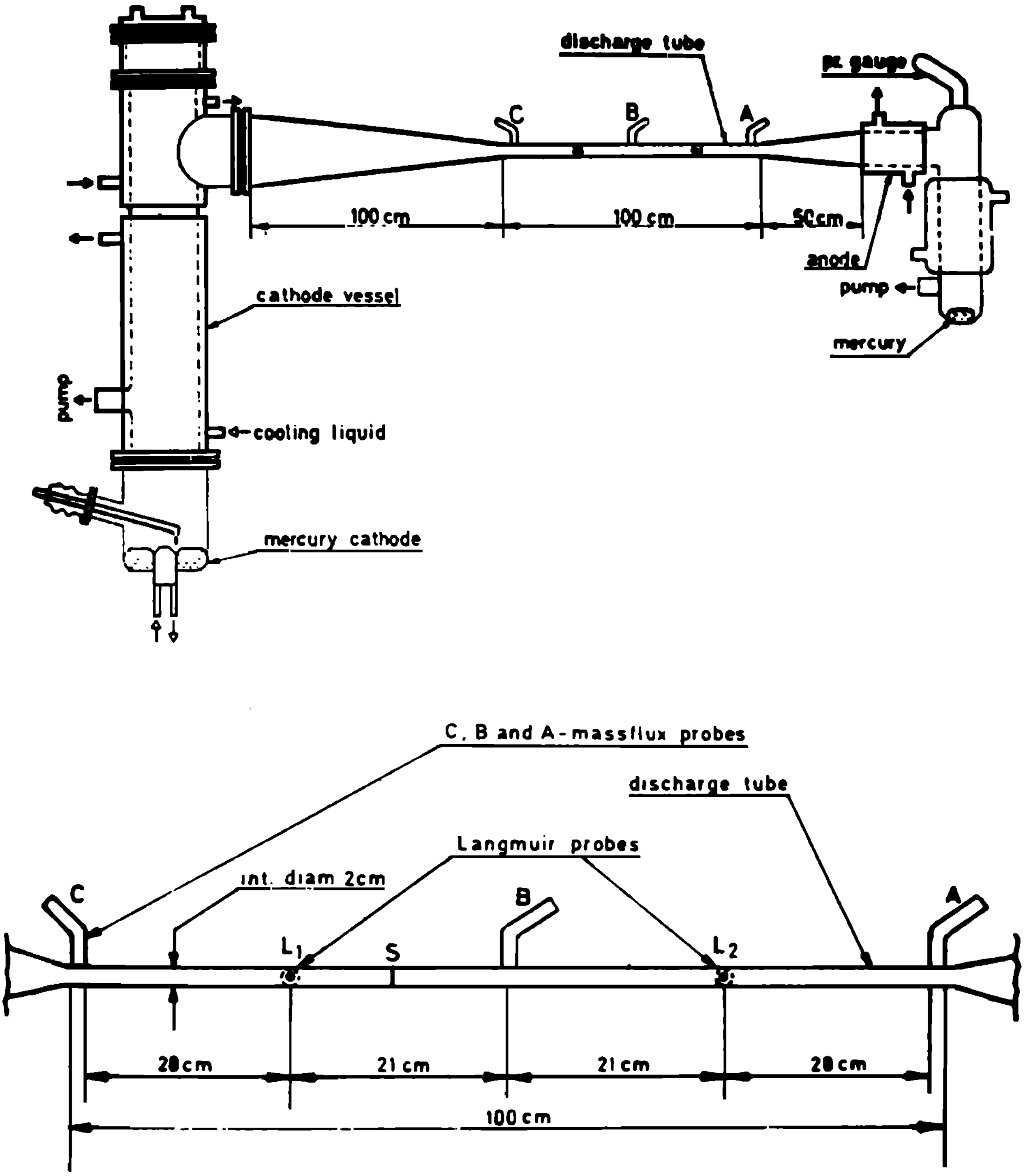

Fig. 3. Discharge device by *Torvén and Babić* [1976].

our investigations on the space research results from our close neighborhood and treat phenomena in more distant regions as extrapolations of those results.

h. Electric Double Layers

Here and in the following paragraphs we shall treat a number of particle related phenomena which are of importance in cosmic plasma physics. They cannot be understood in terms of a formalism in which the electric current has been eliminated.

In the laboratory there are several mechanisms which may produce electric double layers. For example, they are often produced when there is a density or temperature gradient in the plasma. An interesting type of double layer occurs when the electric current density exceeds a certain value which is given by the temperature, density, and degree of ionization of the plasma. Theoretically, we expect a layer of this type to form when the electron drift velocity exceeds the thermal velocity, which means that the usual electric current in the plasma changes into a beam. This gives rise to an instability related to the two-stream instability.

There is extensive literature in this field. We shall concentrate our attention on some recent investigations which have been done especially in order to clarify the cosmic applications. A recent review is given by *Block* [1975], who had

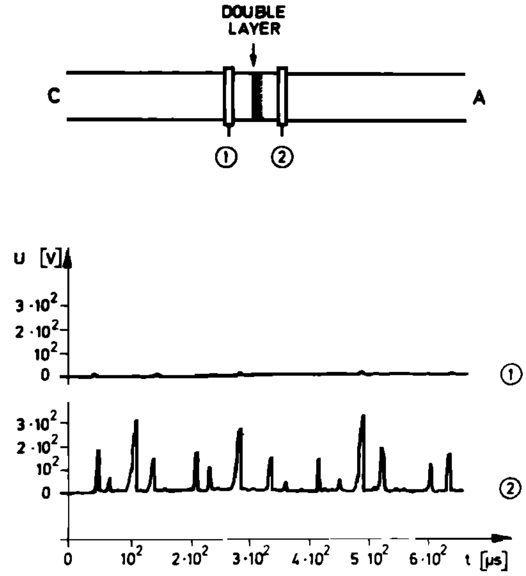

Fig. 4*a*. (Top) Two probes with double layer between them. (Bottom) The voltage between the probes is constant at a certain current (curve 1), but if the current is increased by 5%, the double layer becomes unstable and generates a series of pulses (curve 2).

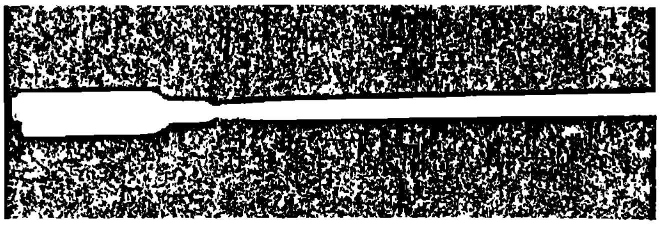

Fig. 4*c*. Photograph of double layer in a discharge tube.

earlier developed a theory of double layer produced by Birkeland currents in the ionosphere-magnetosphere [*Block*, 1972].

Figure 3 shows the experiments of *Babić and Torvén* [1974] and *Torvén and Babić* [1975, 1976], and Figures 4*a* and 4*b* show some of their results. The electron velocity distribution on both sides of a double layer has been measured by *Andersson et al.* [1969]. Figure 5 shows how on the cathode side of the double layer the Maxwellian distribution peaks at 2 eV, but on the anode side this maximum is displaced to 12 eV because the particles have been accelerated in the double layer. At the same time a new peak at 3 eV is produced, which at large distances from the peak becomes the dominant feature.

The experiments demonstrate that the formation of double layers in the laboratory is purely an electrostatic phenomenon and is not primarily produced by a magnetic field. We cannot possibly describe it by a magnetic field related formalism because the electron mass is of decisive importance. It can be observed for currents which are so low that the magnetic field they produce is negligible (even the Larmor radius of the electrons is large).

During the last 5 years there have been a number of magnetospheric observations which indicate the existence of electrostatic double layers in the auroral zone [*Block*, 1972, 1975]. For example, observations show that the auroral zone is often bombarded by almost monochromatic electrons of 1- to 10-keV energy. There are good reasons to believe that these particles have obtained their energy simply by passing through an electrostatic double layer with the voltage ΔV (or a series of double layers with the same total voltage drop). Such layers have recently been observed with barium cloud experiments at altitudes of about 1 R_E [*Haerendel et al.*, 1976; *Wescott et al.*, 1976].

The current causing the double layer in the magnetosphere is of the Birkeland (field aligned) type. The role of the magnetic field is only to confine the current laterally.

Block [1969, 1972, 1975] has discussed the lateral limitation of a double layer (or a distributed change in voltage) and found that the shape of the equipotential surfaces should be as depicted in Figure 6, which is confirmed by observations [*Gurnett*, 1972]. If the current-carrying flux tube below the double layer has the same voltage as the environment, there must be a lateral voltage gradient above the layer. This produces a rotational motion of the plasma (but no motion of magnetic field lines!) around the current-carrying flux tube. In this way the

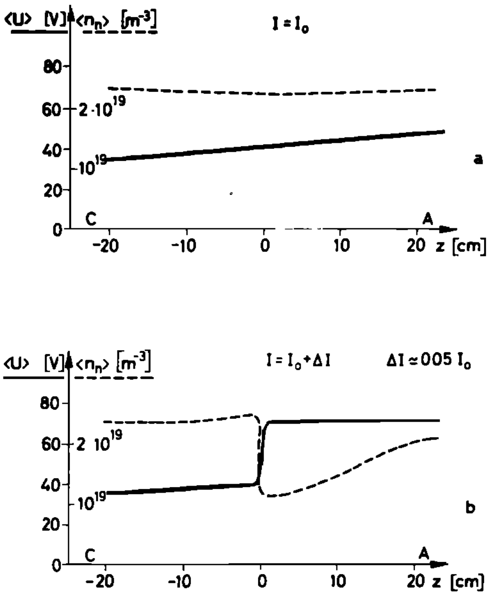

Fig. 4*b*. Density (dashed lines) and voltage (solid lines) at I_0 and $1.05I_0$. A double layer is produced which gives a discontinuity in both density and voltage.

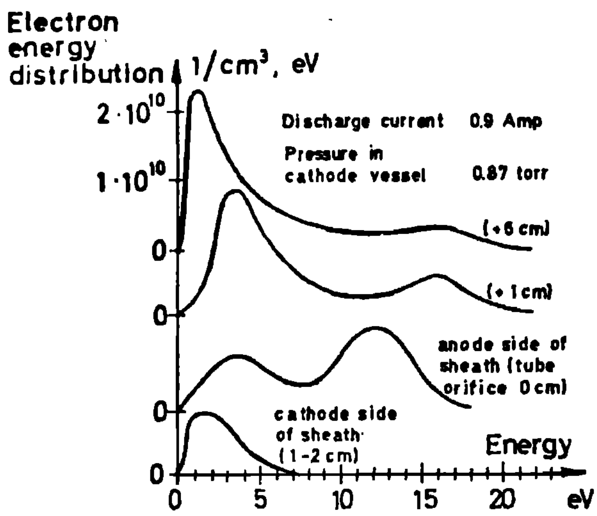

Fig. 5. Electron energy distribution in a laboratory discharge [*Andersson et al.*, 1969]. The big peak near 12 eV in the second lowest curve is produced by the layer, but further down the tube (+1 cm and +6 cm) this peak gradually dispersed, and the beam particles are thermalized.

filamentary current is electrically insulated from the surroundings just as a current in an electric cable. This motivates us to draw electric circuit diagrams for electromagnetic phenomena in space and discuss them with the help of electrotechnical terminology.

i. Energy Release in Double Layers

If a double layer with a voltage difference ΔV has been formed by a current I, a power

$$P = I\Delta V \tag{8}$$

is released in the double layer. This energy is used for accelerating charged particles. It should be stressed that there is no possibility of accounting for the energy of the particles as a result of magnetic field line reconnection or any other mechanism which implies changing magnetic fields in the region of acceleration. In the region of the double layer the magnetic field is almost constant and cannot supply the required energy.

j. Properties of the Local Plasma and of the Circuit

It is important to note that the properties of a double layer depend not only on the properties of the local plasma (in or near the double layer) but on the whole electric circuit in which the plasma current flows [*Babić and Torvén*, 1974].

As we have learned from plasma experiments, a double layer may either be essentially static (although usually associated with noise) or explosive. Suppose the circuit of such an experiment contains an inductance L, a resistance R, an electromotive force V_e, and the plasma (Figure 7). We can represent the plasma by two circuit elements, X referring to the properties of the double layer and Y representing the plasma outside the layer (including the voltage drops near the cathode and anode). For the sake of simplicity we assume that Y consists essentially of a constant voltage drop V'.

The circuit obeys the equation

$$V_e - V' = IR + X(I) + L\, dI/dt \tag{9}$$

X is a complicated function of I, and it also depends on the temperature, density, etc., of the plasma. In general, when I changes by ΔI, X varies by $\Delta X = \rho I$, where $\rho = \partial X/\partial I$.

The dynamical resistance R_d of the circuit is

$$R_d = R + \rho \tag{10}$$

If $R_d < 0$, the current is unstable, and the double layer will either produce oscillations or explode, depending on the higher-order terms in X and the value of L. In the latter case the current may be disrupted and the magnetic energy

$$W_m = \tfrac{1}{2}LI^2 \tag{11}$$

of the circuit delivered to the double layer and the plasma around it.

This shows that the properties of the double layer, including its ability to explode, do not depend only on the properties of the plasma in its close surroundings. We can stabilize the plasma by increasing R and influence its dynamic evolution by changing L. Hence in order to understand the properties of a current-carrying plasma we must take account of the properties of the whole circuit in which the current flows. As this is not done in the magnetic merging theories, we conclude that they give a basically erroneous description of the phenomena, even if a change in the current really produces a field line reconnection (see appendix).

k. Exploding Double Sheaths

As we have seen, the plasma phenomena depend in a decisive way also on the properties of the whole electric circuit. It is well known that all electric circuits containing an inductance L are intrinsically explosive in the sense that if the circuit is disrupted anywhere, the magnetic energy

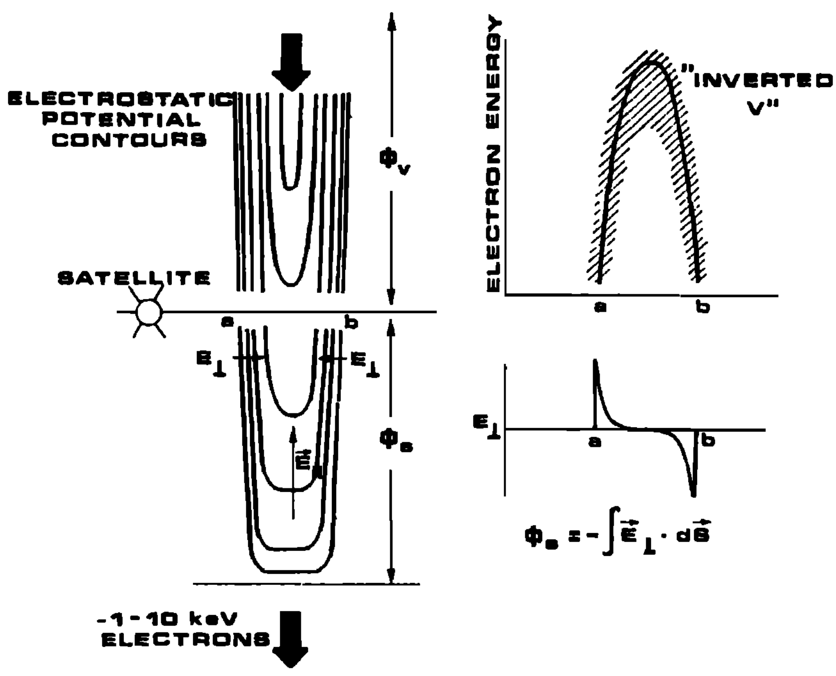

Fig. 6. (Left) Electrostatic potential distribution according to *Gurnett* [1972]. The magnetic field is vertical. The current-carrying flux tube is 'insulated' from the surrounding plasma by a thin cylindrical shell of rotating plasma, which produces a voltage drop which equals the electrostatic drop in the layer. (Right) Observed inverted V events confirm the theory.

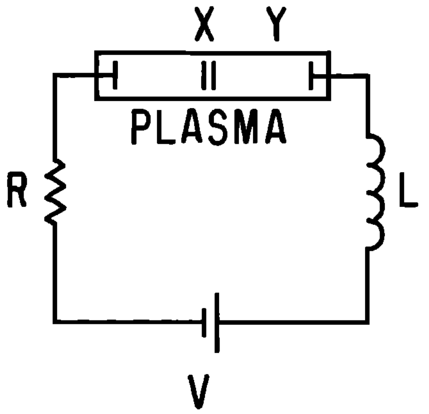

Fig. 7. If a current flows in a plasma, the plasma phenomena depend partially on the outer circuit. If the resistance R is smaller than the negative resistance of the double layer X, the current becomes unstable.

$$W_L = \tfrac{1}{2}LI^2$$

is released at the point of disruption. Further, it is well known from decades of plasma investigation that in the laboratory, certain types of electric double layers may become unstable in the sense that the current is suddenly disrupted. The result is that the energy W_L may be released in the double sheath, where it causes an explosion.

There are good reasons to suppose that many of the explosive events observed in cosmic physics are produced by this mechanism [*Carlqvist*, 1969, 1972, 1973; *Boström*, 1974]. Examples are magnetic substorms, solar flares, and similar phenomena in 'flare stars.' Most recently, it has been suggested by *Ip and Mendis* [1975, 1976] that similar phenomena also take place in the tails of comets and thus lead to the 'folding umbrella' phenomena.

l. General Properties of the Electric Circuits

In the simplest case our circuits contain four circuit elements: an emf V_0, an inductance L, a resistor R, and an electrostatic double layer D. If the double layer explodes and disrupts the current when it has reached the value I_0, the circuit has the properties illustrated by Figure 8. When it is switched on, the current increases at the rate $dI/dt = V_0/L$. After an infinite time it would reach the value $I_R = V_0/R$ if $I_0 > I_R$.

If

$$I_0 < I_R = V_0/R \qquad (12)$$

explosions occur at regular intervals T, which if $I_0 << I_R$, are given by

$$T = LI_0/V_0 \qquad (13)$$

Repetitive events are often observed (magnetic substorms, solar flashes, sometimes solar flares). In all of these cases the repetitive properties may be due to the properties of this simple circuit. The energy which is dissipated at the explosions derives from the kinetic energy of the plasma motions and the magnetic field.

There is also another important way in which the energy $\tfrac{1}{2}LI^2$ of the circuit can be dissipated. If an electric current flows in a circuit, it exerts an electrodynamic pressure so that the circuit loop has a tendency to expand. In cosmic plasmas this pressure is usually balanced by other forces (e.g., other electromagnetic effects, gravitation, gas pressure). If the current increases above a certain value, its electromagnetic pressure may be so large that the balancing effects do not suffice and the current loop may explode. An example of this is the rising prominences. In this case, part of the circuit energy is converted into kinetic energy.

2. ELECTRIC CIRCUITS

a. Survey of the Models

In this part we shall apply the general principles we have discussed in section 1 by constructing a number of simplified models of electric circuits. We will find that these are essentially of four different types. One model of each of the four types can be based on our knowledge of regions which are reasonably well studied by in situ measurements.

The best-explored circuit is the auroral circuit of which we make a simplified model called the auroral circuit I (ACI). This does not give the best possible picture of the currents in the auroral zone as we know them, but because of its simplicity it is useful. The real current system can be regarded as a superposition of two ACI's and another circuit called ACII. The ACI is applied to the model of solar flares and to the cosmogonic problem of angular momentum transfer.

The third model is called the heliospheric circuit (HC) and describes the currents in interplanetary space which are also reasonably well known (in certain regions). This model is tentatively applied to the Jovian magnetosphere, and it is shown that the Jovian current system may be of a similar character. Because there are not yet any plasma measurements in the Jovian surroundings, this conclusion is uncertain. Moreover, as in the earth's magnetosphere, the complete current system is certainly too complicated to be represented by one simple model.

The fourth model, called the tail circuit (TC), is based on the investigations of the earth's magnetotail. When a substorm occurs, the tail current system gets connected with the auroral zone, and the TC should be substituted by the more complicated Boström model for substorms [*Boström*, 1974]. This can be depicted as a combination of the TC and ACII. The TC is applied to the magnetopause. Further, the TC is applied to cometary tails. Unfortunately, we have no in situ measurements of comets, but as *Ip and Mendis* [1976] have shown, there is such a striking similarity between the current system in cometary tails and the earth's magnetotail that we may consider the cometary phenomena as the magnetotail phenomena viewed from a distance.

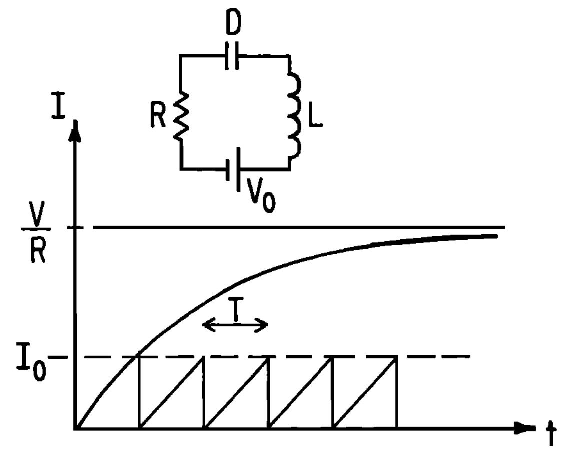

Fig. 8. The circuit of Figure 7 gives repetitive explosions with a time constant $T = LI_0/V_0$. For every disruption the energy $1/2LI_0^2$ is dissipated at X.

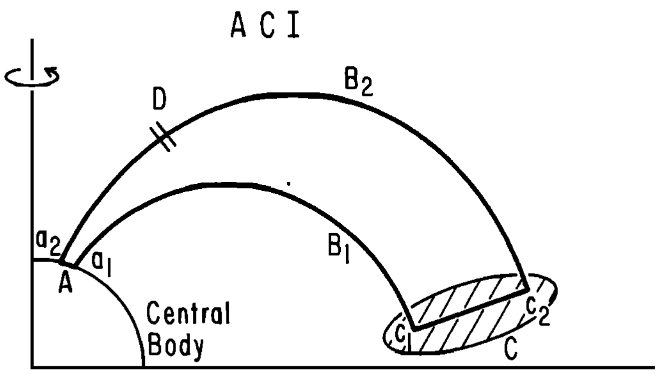

Fig. 9. Auroral circuit I. Currents along the magnetic field lines B_1 and B_2 close through the upper atmosphere at A and through the magnetospheric plasma at C. The emf is produced by motion at A and C. The current may produce one or more electrostatic double layers D.

b. *Auroral Circuit I (ACI)*

The circuit consists of the following elements (Figure 9).

Atmospheric region. The currents flowing in the ionosphere form in reality a complicated system. What is of interest for the ACI model is essentially that due to the rotation of the earth, an emf of

$$V_A = \int_{a_1}^{a_2} \mathbf{v} \times \mathbf{B} \cdot d\mathbf{s} \tag{14}$$

is produced (**v** is the velocity of the ionosphere due to the earth's rotation, and **ds** is a line element).

Birkeland region. This is characterized by Birkeland currents along the field lines. There is no emf, but one or more electrostatic double layers D_n, each with voltage drops ΔV_n, may be produced by the current. The total voltage drop in them is $V_D = \sum \Delta V_n$. The region consists of two parts B_1 and B_2 carrying currents in opposite directions, and there may be double layers in both. Instead of double layers there may be distributed regions with $E_\parallel \neq 0$.

Cloud region. In this region a plasma cloud moving with velocity v_c produces an emf of

$$V_c = \int_{c_1}^{c_2} \mathbf{v}_c \times \mathbf{B} \cdot d\mathbf{s} \tag{15}$$

In the circuit that we are considering there flows a current which is given by

$$V_A + V_C - \sum \Delta V_n = RI + L\, dI/dt \tag{16}$$

where $R = R_A + R_B + R_C$ is the ohmic resistance of the circuit.

The inductance L is given by

$$\tfrac{1}{2} L I^2 = \int B^2/8\pi \, d\tau \tag{17}$$

where B is the magnetic field produced by I in the volume element $d\tau$.

The total magnetic field in the region is produced by the currents I_E in the interior of the earth and the current I. If I_E flows in a circular loop in the center of the earth, it produces a magnetic dipole field.

Figure 9 shows a linear current in a meridional plane, but the current may also form a sheath, extending over a certain range of longitudes, which may be as large as 2π. This circuit originally had a speculative character, but space measurements, especially those by *Zmuda and Armstrong* [1974], have confirmed that it really constitutes a first approximation to the current system in the auroral zone [*Boström*, 1974, 1975*b*]. See Figures 10 and 11.

The ACI is also applicable to field-aligned currents in the Jovian magnetosphere that are produced by the motion of its satellites [*Kivelson and Winge*, 1975].

Invisible transfer of energy. It is important to note that the auroral circuit transfers energy from the moving plasma cloud C to the region of release D through electric currents in B_1 and B_2 and an electric voltage difference between B_1 and B_2. Both the current and the voltage difference are difficult to detect even by in situ measurements. From a distance it is almost impossible to observe them. What we may observe from a distance is that energy disappears in a region C (e.g., that the velocity of the cloud is retarded) and that energy is released in another region D (e.g., by the emission of radiation from this region). Hence we have a mechanism of 'invisible' transfer of energy over a large distance. As we shall see in section 2*i*, this may give us the key to energy release in double radio stars.

An invisible transfer is a characteristic of many electric circuits. For example, when we observe the earth from a satellite or an airplane, we easily see street lights dissipating electric energy, and we may also see hydroelectric power stations generating it, but it is almost impossible to observe how the energy is transmitted. In sections 1*h*, 1*i*, and 1*j* we learned that in important respects the transfer of energy in cosmic physics is similar to the electrotechnical transfer.

c. *Auroral Circuit II (ACII)*

Electric currents along the field lines may also form a somewhat different circuit, which we shall call auroral circuit II (ACII) (see Figure 12). The inward and outward currents intersect the ionosphere at points at the same latitude but at different longitudes. The emf may be produced in the ionosphere by north-south directed winds or in the equatorial plane by radial plasma flow. In two important cases (magnetic substorms and the folding umbrella phenomena in comets) the emf in the equatorial plane is produced between c_1 and c_2 by disruption of a current in another circuit. The total current

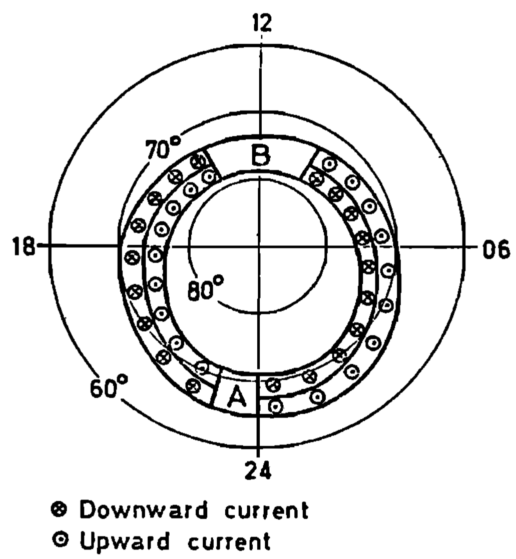

Fig. 10. Vertical currents in the auroral zone observed by *Zmuda and Armstrong* [1974]. On the evening side the downward currents flow at a lower latitude than the upward currents; on the morning side the directions are reversed.

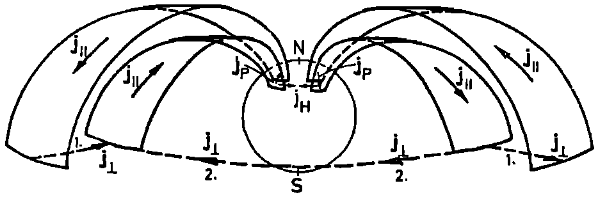

Fig. 11. Three-dimensional picture of the currents of Figure 10 [*Boström*, 1975*b*]. This current system consists of one ACI in the evening and one, with reverse direction, in the morning.

system in the auroral zone seems normally to be due to a superposition of two ACI, one in the evening and one in the morning side of the earth, and one ACII system, joining these two systems on the nightside [*Boström*, 1974].

Ultimately these circuits get their energy from the solar wind, and the transfer to the magnetosphere takes place in the tail and magnetopause systems [see *Boström*, 1974, 1975*c*]. Hence the complete solar wind–magnetosphere–ionosphere must be a rather complicated combination of these circuits.

d. Application to Angular Momentum Transfer in the Cosmogonic Problem

The ACI gives a transfer of angular momentum between the central body and a plasma cloud in its surroundings of the type which is needed in order to understand how planets and satellites were put into orbit when the solar system originated. The application of the ACI leads to the theory of the free-wheeling plasma ('partial corotation') [*Alfvén and Arrhenius*, 1976, chap. 16, 17; *Alfvén*, 1976]. See Figure 13. The detailed structure of the Saturnian rings and the asteroidal main belt can be explained by this theory. Hence the ACI seems to have been of fundamental importance for the transfer of angular momentum during cosmogonic times.

It is important to note that $f_g > f_c$, which means that the free-wheeling plasma is partially supported by the magnetic field. A free-wheeling plasma can never 'inflate' a magnetic dipole field.

e. Solar Prominences

With a slight modification the ACI model can be applied to solar prominences. We substitute a sunspot for the central body A, cancel the region B_1, and let C represent the solar surface. A solar flare occurs when the double layer D explodes [*Carlqvist*, 1969, 1972, 1973].

f. Solar Activity

Generalizing the model still more, we may ask whether all the phenomena referred to as solar activity are not best clarified by a current model. In fact, because of the presence of magnetic fields and motions in the solar photosphere, the sun should have a fluctuating voltage over its whole surface. If a magnetic field line runs between two points a and c of voltages differing by ΔV, a current along a magnetic field line abc may be produced which closes through a diffuse current cda at the surface or below (Figure 14).

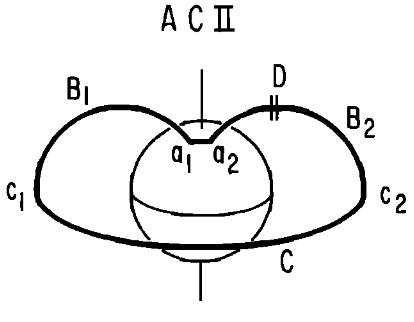

Fig. 12. Auroral circuit II. The circuit is similar to ACI with the current-carrying field lines B_1 and B_2 at the same latitude but different longitudes. Curve c_1c_2 is part of a circle in the equatorial plane; a_1a_2 is part of the auroral zone.

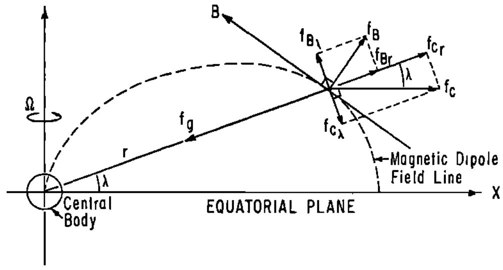

Fig. 13. Because of the occurrence of double layers D in ACI a rotating central body can never bring a surrounding plasma cloud into complete corotation. The cloud instead reaches a free-wheeling state, which is determined by the equilibrium between the centrifugal force f_c, the gravitation f_g, and the electromagnetic force f_b. Under free-wheeling conditions, f_c is always smaller than f_g, and the plasma can never 'inflate' the magnetic field.

All filamentary phenomena in the solar atmosphere are probably produced by currents in this way. Small-scale circuits produce spicules in the chromosphere; large circuits produce prominences, coronal streamers, and polar plumes.

g. Heliospheric Circuit (HC)

In its simplest possible version this model consists of a central body magnetized by a current I_E (as in the ACI), a radial current I_0 flowing in the equatorial plane and extended uniformly over 2π in longitude, and two axial currents, each $\frac{1}{2}I_0$, flowing in opposite directions. The current I closes at infinity. The emf is due to the rotation of the central body (unipolar induction).

In a cylindric coordinate system (r, ϕ, z) the magnetic field from I_0 is

$$\begin{aligned} B_\phi &= I_0/r \qquad z > 0 \\ B_\phi &= -I_0/r \quad z < 0 \end{aligned} \tag{18}$$

This extreme simplification makes the model unrealistic, and we shall approach reality by a somewhat more realistic model, called the heliospheric circuit (HC) (see Figure 15), by adding a system of circular currents I_ϕ in the equatorial plane so that the magnetic field lines close to the equatorial plane have the spiral shape which is produced by the solar wind in combination with the solar rotation.

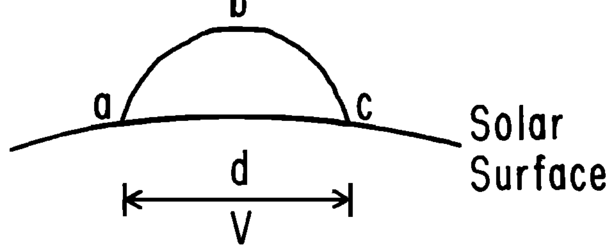

Fig. 14. Circuit of general solar activity. Random motions v in the photosphere produce an emf of $V = \int_{adc} \mathbf{v} \times \mathbf{B} \cdot d\mathbf{s}$ between the two intersections a and c of a magnetic field line with the photosphere. V drives current along the field line abc. Mostly only the parts of the current filament near a and c are observed. This is likely to be the basic phenomenon for prominences and spicules.

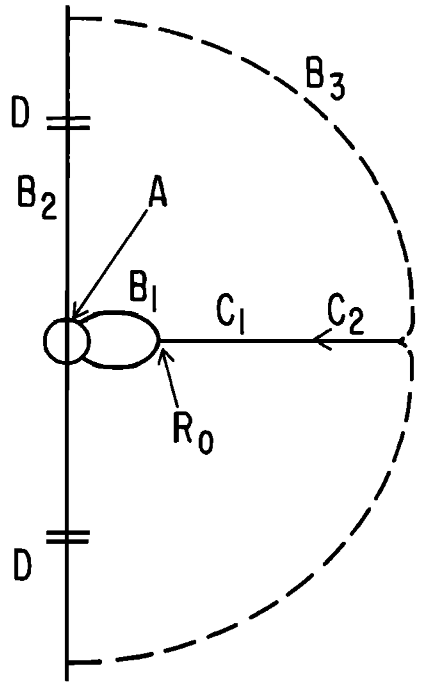

Fig. 15*a*. Heliospheric circuit. The sun acts as a unipolar inductor (A) producing a current which goes outward along the axis (B_2) and inward in the equatorial plane C_2, C_1 and along the magnetic field lines B_1. The current closes at large distance (B_3).

If the solar wind flows radially with the constant velocity v_s and the magnetic field points in the direction of the solar wind seen from a coordinate system which rotates with the angular velocity Ω of the sun, we have $v_\phi = r\Omega$. For the magnetic field B_z and the surface current density i,

$$\begin{aligned} B_r &= B_0(r_0/r)^2 \\ B_\phi &= B_r v_\phi/v_s = B_0 r_0/r \\ i_r &= (I_0/2\pi r_0)(r_0/r) = i_0 r_0/r \\ i_\phi &= i_r(v_s/v_\phi) = i_0(r_0/r)^2 \end{aligned} \qquad (19)$$

where $r_0 = v_s/\Omega$ is the solar distance where the field spiral makes a 45° angle with the vector radius, B_0 is the radial magnetic field, and $i_0 = I_0/2\pi r_0$ is the radial current density at this distance. Further, we have $I_0 = 2\pi r_0 i_0 = B_0 r_0$, and with $B_0 = 2 \times 10^{-5}$ G and $r_0 = 1.5 \times 10^{13}$ cm we find $I_0 = 3 \times 10^8$ esu $= 3 \times 10^9$ A = 3 GA.

An essential difference between ACI and HC is due to the solar wind, which produces the tangential current system (equivalent to a stretching out of the magnetic field lines of the original dipole field). Further, in the ACI the main emf is due to the tangential component of the magnetospheric convection, whereas the electromotive force due to the earth's rotation is of minor importance. In the case of the sun the plasma motion is radial, so that **v** × **B** in section 2*b* has no radial component. Hence the main emf is due to the sun acting as a unipolar inductor.

In the ACI the current is not large enough to cause more than a small perturbation of the magnetic field. At large currents a circuit has a tendency to expand. If the auroral circuits of both hemispheres expand, they will jointly form a current system like HC. The current layer should have an inner limit, which we denote by R_0. Inside R_0 we let the current I continue along magnetic field lines to the central body, similar to the HC.

Regions A and B_1 are the same as in ACI. Region B_2 is moved toward the axis and may be depicted either as a current with infinite density flowing exactly on the axis or, more realistically, as a current flowing in a certain region near the axis.

Because of i_ϕ the region C consists now of two regions. In the inner one (C_1) the magnetic field is predominantly radial ($B_r > B_\phi$) and the current predominantly tangential ($i_\phi > i_r$), whereas in the outer one (C_2) the reverse is true. The limit between C_1 and C_2 occurs at r_0, where the field lines and the current lines both make a 45° angle with the vector radius. The total magnetic field decreases as r^{-3} in B_1, as r^{-2} in C_1, and as r^{-1} in C_2.

The radial current in the equatorial plane and the two axial currents may go to infinity, becoming increasingly diffuse, or they may connect through currents in the region B_3, which either may be filamentary or forming a sheath.

'Sector structure' and the equatorial current layer. Spacecraft measurements, which so far have been restricted to the neighborhood of the ecliptic plane, have revealed that the interplanetary magnetic field is directed inward in certain regions, whereas in other regions it is outward. The regions are separated by very sharp boundaries, obviously current layers. It was first thought that these currents flowed perpendicular to the ecliptic plane and were due to a 'sector structure' of both interplanetary space and solar atmosphere. From a current point of view, this interpretation looked absurd because it implied that, for example, at the earth's distance the large currents in the boundary layers should be connected along meridional planes to the sun. It seemed more likely that the observed current layers should be due to the theoretically expected equatorial current layer of Figure 15 and that the change in field direction should be due to the position of the earth in relation to the current layer.

Rosenberg and Coleman [1969] have given convincing observational evidence for the view that this theoretical picture is correct [see *Rosenberg*, 1970]. The phenomenon, which is still erroneously referred to as the 'sector structure' of the solar wind, is due to relatively small up and down displacements of the solar equatorial current layer. It is similar to the wave motion of the skirt of a spinning ballerina. We shall in the following neglect the ballerina effect and consider the magnetic conditions near the equatorial plane to be produced by a plane current layer.

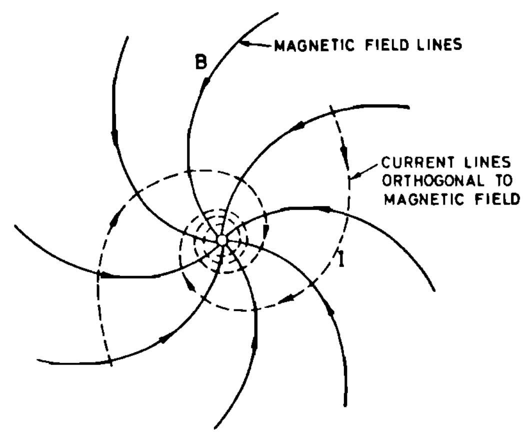

Fig. 15*b*. Magnetic field lines somewhat above the equatorial plane and current lines in the equatorial plane. Close below the equatorial plane the field lines have the same geometry but opposite direction.

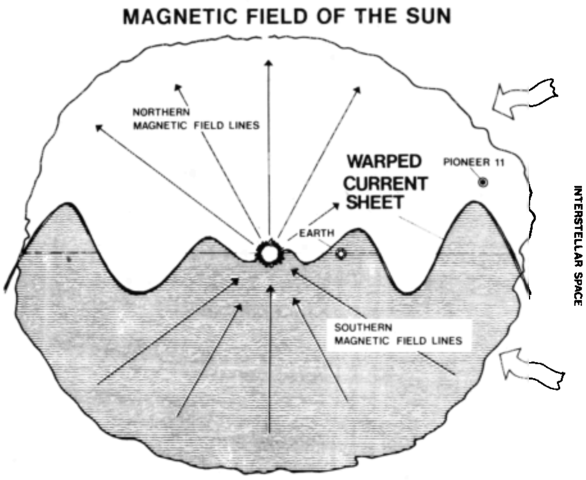

Fig. 15*c*. Current sheath in the equatorial plane derived from space measurements [*Smith et al.*, 1976]. When the current sheath waves up and down like the skirt of a ballerina, the interplanetary magnetic field changes sign.

Properties of HC. The model has the following properties, which should be compared with observed properties of the sun and the heliosphere.

The central body acts as a unipolar inductor, and the emf is produced in the region A. The mechanical force on the solar atmosphere $df = \mathbf{I} \times \mathbf{B} \cdot \mathbf{ds}$ tends to retard the rotation of the central body. The current transfers angular momentum from the central body to the surrounding plasma, and most of it may be received by the innermost part of region C_1. Hence we have a retarding force applied to the polar region and an accelerating force applied to the highest layers of the solar atmosphere in the equatorial region. This should produce a nonuniform rotation of the sun of the type which is observed (angular velocity decreasing with increasing latitude and increasing with height in the atmosphere near the equator).

In the region B_1 the currents are field aligned. It seems to be a general rule in cosmic physics that field-aligned currents manifest themselves as luminous filaments. If the current in B_1 is spread over an extended region, we should expect filaments similar to the equatorial streamers in the solar corona.

Similarly, in the B_2 region the vertical currents near the solar surface may produce the polar plumes in the corona.

The model predicts that there should be currents near the axis strong enough to match the current in the equatorial plane. Such currents should be observed when a spacecraft is sent to the high-latitude regions. It is an open question to what extent they flow very close to the axis. They may be distributed over a large region and in part flow at medium latitudes also.

It should be pointed out that electrostatic double layers may be formed, perhaps especially by the axial currents. This means that we may have regions D far away from the sun, where energy is released without any observable indication of how it is transferred. This is analogous to the release of energy at the electrostatic double layers in the auroral zones. If a double layer is formed far out from the sun, it may emit radio waves or plasma waves which could be detected.

h. Application to the Jovian Magnetosphere

If we want to construct a model of the Jovian magnetosphere, it is reasonable to start by looking for similarities with the terrestrial or solar surroundings. It is obvious that the Jovian magnetosphere is drastically different from the earth's magnetosphere, but it is less obvious that the difference with the heliosphere is very large. Hence we shall here investigate to what extent the HC is applicable to the Jovian magnetosphere. This means that we try to apply the rather detailed knowledge that we have of the conditions in interplanetary space to the less well-known conditions around Jupiter. We find that the HC model is reconcilable with the following observational facts.

Jupiter has a nonuniform rotation like the sun, and this may be a result of our current system acting in the region A (see Figure 15*a*).

The Jovian magnetic field consists of three different regions. Up to about 10 R_J it is given by the internal currents in Jupiter [*Smith et al.*, 1976]. We identify this region with B_1.

In the region between 10 R_J and 50–60 R_J the magnetic field is a 'stretched-out' dipole field which can be depicted as deriving from circular currents in the equatorial plane. This is in agreement with the currents in the C_1 region. However, the measurements indicate that most of the tangential current flows between 30 and 60 R_J, so perhaps the limit between B_1 and C_1 should be as far out as 30 R_J. The HC model requires also a radial current in the field, and according to Smith et al. the measurements indicate the existence of a radial component.

In some cases the magnetic field lines outside this region point increasingly westward. This agrees with the C_2 region in our model, but the outer magnetosphere is obviously very perturbed. The limit between C_1 and C_2 is far out, and we should possibly put $r_0 \approx 80\ R_J = 6 \times 10^{11}$ cm. As $\Omega = 1.6 \times 10^{-4}$, we find $v = 10^8$ cm/s. This is of the same order of magnitude, or even larger, than the solar wind.

If we accept the similarity between the heliosphere and the Jovian magnetosphere, there must be a Jovian wind emitted with properties similar to the solar wind. This requires a strong heating of the uppermost layers of the Jovian atmosphere, perhaps by the current system that we consider. The density of the Jovian wind must be very low [see *Goertz,* 1976].

This picture is an alternative to the model by *Hill et al.* [1974], in which the centrifugal force of a corotating plasma is supposed to be responsible for the outflow. However, in the absence of frozen-in field lines, a synchronous corotation is not very likely to be established. For a partial corotation (freewheeling plasma) depicted in Figure 13 the centrifugal force is always smaller than the gravitation and could not 'inflate' the magnetic field. A decision between different mechanisms cannot be made until plasma measurements of the Jovian magnetosphere are available.

Even if the analogy between the heliosphere and the Jovian magnetosphere can be helpful, the Jovian conditions are obviously too complicated to be described in detail by any simple model.

i. Application to the Double Radio Sources

A most puzzling phenomenon is the double radio sources, which usually have a visual galaxy almost exactly halfway between each source. Hypotheses concerning their energy source are essentially of two types: The radio sources may get their energy from an object in the center of each of the radio-emitting regions, although no such object has been found; or the emitting clouds may be shot out symmetrically in two directions from the central galaxy, but then their initial energy must be enormous in order to supply energy to the radio objects during a long period of time.

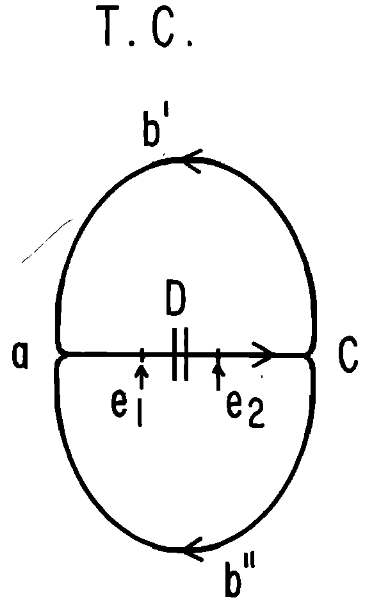

Fig. 16. Tail circuit. The line elements $ab'c$ and $ab''c$ are located in the solar wind, and aDc are in the magnetotail. The polarization of the solar wind produces an emf of $\int_{ab'c} \mathbf{v} \times \mathbf{H} d\mathbf{s}$, which gives a current in the neutral sheet in the tail. This current system determines the magnetic field in the tail. An electric double layer may be formed at D, which, if it is exploding, produces a magnetic substorm, which may be repetitive according to Figure 8.

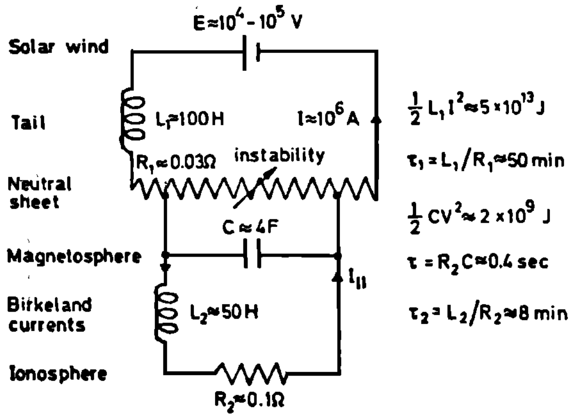

Fig. 17. The explosion of D in Figure 14 causes a current in ACII (Figure 10). The properties of the total circuit are represented by this diagram [*Boström*, 1974].

As soon as we describe cosmic phenomena by current models, we get another mechanism for energy transfer over large distances. As we have seen from the ACI, kinetic energy is transferred from C and released in a double layer D. The transfer occurs by means of electric currents and an electrostatic potential difference: neither of which is very easy to detect, not even by in situ measurements. What might be most easily observed from a large distance is essentially that kinetic energy disappears from a certain region C and that there is a production of accelerated particles or oscillations in one or more regions D, which may be very far away from the energy source.

As the visual galaxy halfway between the two radio stars is probably magnetized, it may act as a unipolar inductor, and the HC model may be applicable. This means that we should expect currents to flow in opposite directions along the rotational axis of the galaxy as in Figure 15*a*. Double layers may be formed in two or several symmetrically located regions D, and the energy of the rotation of the galaxy may be transferred by the electric circuit to these regions. Because of the currents there must be strong magnetic fields in these regions so that electrons accelerated in the double sheaths may produce the synchrotron radiation, which the radio stars emit.

j. Tail Circuit (TC)

The circuit of the current which magnetizes the magnetotail is in principle very simple (Figure 16). It consists of a sheet in which a current flows from a to c in a plasma which, in relation to the earth, is at rest or moves slowly. The circuit is closed by currents $cb'a$ and $cb''a$ flowing in the solar wind, which has the velocity v perpendicular to the plane of the figure and a magnetic field B. The emf is

$$V = \int_{cb'a} \mathbf{v} \times \mathbf{B} \cdot d\mathbf{s}$$

and when B has a southward component close to the magnetotail it produces a current system as shown in the figure. The tail current may also close through currents to infinity in the plane ac.

In the sheet an electric double layer D may be formed, and it frequently explodes. Because of the inductance of the circuit a large voltage difference is produced between e_1 and e_2, and the current is 'reconnected' over the auroral zone through an ACII. The total circuit according to *Boström* [1974] is shown in Figure 17.

k. Application to the Magnetopause

The same circuit is also applicable to the magnetopause. The main difference is that in the tail the current flows in the equatorial plane but in the magnetopause it flows in a plane

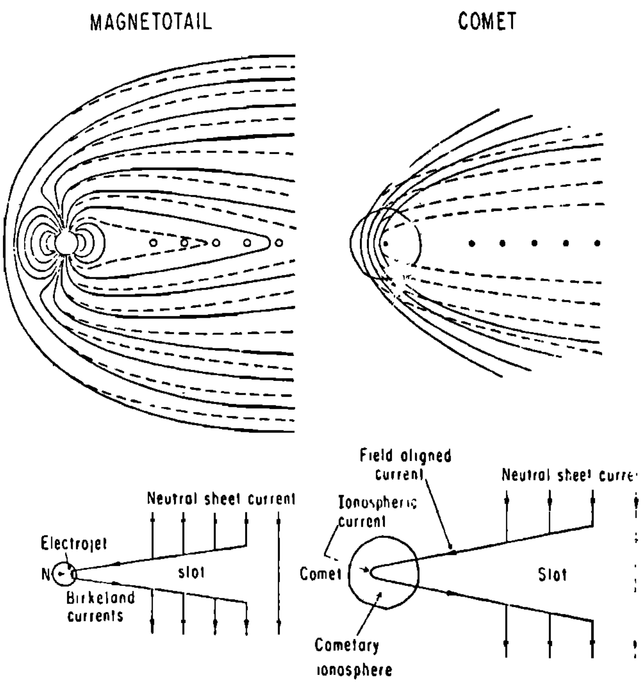

Fig. 18. Similarity between the magnetosphere and a comet [*Ip and Mendis*, 1976]. Current disruption which causes repetitive substorms in the magnetosphere (compare Figure 8) also causes the folding umbrella phenomenon in comets and simultaneous brightening of the coma.

perpendicular to the equatorial plane (in reality, this plane is a more complicated curved surface). For some reason the magnetopause current system seems never to be disrupted.

The currents in the solar wind flow not only to the north and to the south of the magnetopause but also sunward. In fact, what is usually referred to as 'bow shock' is a current sheet (as seen from the difference in B on both sides of it). It seems likely that this current connects to the magnetopause current.

The tail and magnetopause current systems transfer energy from the solar wind to the magnetosphere. This energy is sufficient (10^{10}–10^{11} W) to account for all the dissipation in the magnetosphere [*Alfvén and Fälthammar,* 1971]. An energy transfer through viscous effects or through magnetic merging or some other mechanism is unnecessary and counterindicated.

l. *Application to Comets*

In a recent paper, *Ip and Mendis* [1976] have demonstrated that the cometary tails are similar to the magnetotail in important respects (Figure 18). The folding umbrella phenomenon in comets is likely to be caused by a current disruption of the same type as is causing magnetic substorms.

APPENDIX

The following are conclusions about magnetic merging.

Stationary Magnetosphere

Magnetic field is static.

Electric field is static.

Electric currents are constant.

Plasma flow is stationary.

Particle energy $W = W_0 \pm e \int \mathbf{E} \cdot d\mathbf{s}$.

No magnetic field lines merge.

Hence magnetic merging theories are not applicable (but they may be applicable to nonstationary cases).

Nonstationary Magnetosphere

If electric current flows in a plasma, the plasma properties depend not only on the local parameters but also on the whole circuit.

Hence even under nonstationary conditions, magnetic merging theories are erroneous.

Acknowledgments. This work was supported in part by the following grants: NASA-NSG-7102 of the NASA Planetology Program, NASA-NGR-05-009-110 of the NASA Physics and Astronomy Program, and NSF-MPS74-23501 and NSF-MPS74-21195 of the Solar System Astronomy Program of the NSF.

BIBLIOGRAPHY

Alfvén, H., *Cosmical Electrodynamics,* Oxford at the Clarendon Press, London, 1950.

Alfvén, H., Electric current structure of the magnetosphere, in *Physics of the Hot Plasma in the Magnetosphere,* edited by B. Hultqvist and L. Stenflo, Plenum, New York, 1975.

Alfvén, H., On frozen-in field lines and field line reconnection, *J. Geophys. Res., 81,* 4019, 1976.

Alfvén, H., and G. Arrhenius, *Evolutionary History of the Solar System,* D. Reidel, Hingham, Mass., 1975.

Alfvén, H., and G. Arrhenius, Evolution of the solar system, *NASA Spec Publ, 345,* 1976.

Alfvén, H., and C.-G. Fälthammar, *Cosmical Electrodynamics, Fundamental Principles,* Oxford University Press, New York, 1963*a*.

Alfvén, H., and C.-G. Fälthammar, *Cosmical Electrodynamics,* 2nd ed., p. 161, Oxford at the Clarendon Press, London, 1963*b*.

Alfvén, H., and C.-G. Fälthammar, A new approach to the theory of the magnetosphere, *Cosmic Electrodynamics, 2,* 78, 1971.

Andersson, D., M. Babić, S. Sandahl, and S. Torvén, On the maximum current carrying capacity of a low pressure discharge, in *Proceedings of the Ninth International Conference on Ionized Gases,* p. 142, Editura Academii Republicii Socialista Romania, Bucharest, 1969.

Armstrong, J. C., Field-aligned currents in the magnetosphere, in *Magnetospheric Physics,* edited by B. M. McCormac, pp. 155–166, D. Reidel, Hingham, Mass., 1974.

Babić, M., and S. Torvén, Current limiting space charge sheaths in a low pressure arc plasma, *Rep. TRITA-EPP-74-02,* Roy. Inst. of Technol., Stockholm, Jan. 1974.

Block, L. P., Some phenomena in the polar ionosphere, *Rep. TRITA-EPP-69-30,* Roy. Inst. of Technol., Stockholm, 1969.

Block, L. P., Potential double layers in the ionosphere, *Cosmic Electrodynamics, 3,* 349–376, 1972.

Block, L. P., Double layers, in *Physics of the Hot Plasma in the Magnetosphere,* pp. 229–249, Plenum, New York, 1975

Boström, R., Magnetosphere-ionosphere interactions, some significant achievements 1973–1975, Report of Subdivision 7 of IAGA Division III, *Rep. TRITA-EPP-75-17,* Roy. Inst. of Technol., Stockholm, 1975*a*.

Boström, R., Mechanisms for driving Birkeland currents, in *Physics of the Hot Plasma in the Magnetosphere,* Plenum, New York, 1975*b*.

Boström, R., Current systems in the magnetosphere and ionosphere, Lecture of the Eiscat Summer School, Tromsö, Norway, 8–13 June, *Rep. TRITA-EPP-75-18,* Roy. Inst. of Technol., Stockholm, 1975*c*.

Boström, R., Ionosphere-magnetosphere coupling, in *Magnetospheric Physics,* edited by B. M. McCormac, pp. 45–59, D. Reidel, Hingham, Mass., 1974.

Carlqvist, P., Current limitation and solar flares, *Solar Phys., 7,* 377, 1969.

Carlqvist, P., On the formation of double layers in plasmas, *Cosmic Electrodynamics, 3,* 377, 1972.

Carlqvist, P., Double layers and two-stream instability in solar flares, *Rep. TRITA-EPP-73-05,* Roy. Inst. of Technol., Stockholm, 1973.

Coleman, P. J., and R. L. Rosenberg, Heliographic latitude dependence of the dominant polarity of the interplanetary magnetic field, *J. Geophys. Res., 74,* 5611, 1969.

Dawson, J., Some investigations of nonlinear plasma behaviour on one-dimensional plasma models, paper presented at 3rd Conference on Plasma Physics, Int. At Energy Agency, Novosibirsk, USSR, 1968.

De Barbieri, O., The space structure of the ambipolar potential in mirror machines, in *Fifth European Conference on Controlled Fusion and Plasma Physics,* vol. 1, p. 87, Centre d'Etudes Nucléires de Grenoble, Grenoble, France, 1972.

Geller, R., N. Hopfgarten, B. Jacquot, and C. Jacquot, Electric fields parallel to the magnetic field in a strong anisotropic plasma in a magnetic mirror field, *Rep. EUR-CEA-FC-699,* Dep. de Phys. du Plasma et de la Fusion Contr., Ass. Euratom C, Fontenay-aux-Roses, France, 1973.

Goertz, C. K., The current sheet in Jupiter's magnetosphere, *J. Geophys. Res., 81,* 3368–3372, 1976.

Gurnett, D. A., Electric field and plasma observations in the magnetosphere, in *Critical Problems of Magnetospheric Physics,* edited by E. R. Dyer, p. 123, Inter-Union Committee on Solar-Terrestrial Physics, National Academy of Sciences, Washington, D. C., 1972.

Haerendel, G., et al., First observation of electrostatic acceleration of barium ions into the magnetosphere, European Programmes on Sounding-Rocket and Balloon Research in the Auroral Zone, *Rep. SP-115,* pp. 203–211, Eur. Space Agency, Sci. and Tech. Publ. Branch, ESTEC, Noordwijk, Netherlands, Aug. 1976.

Hill, T. W., A. J. Dessler, and F. C. Michel, Configuration of the Jovian magnetosphere, *Geophys. Res. Lett., 1,* 3–6, 1974.

Hopfgarten, N., R. B. Johansson, B. Nilsson, and H. Persson, Penning discharge in a strongly inhomogeneous magnetic mirror field, *Phys. Fluids, 11,* 2277, 1968.

Hopfgarten, N., R. B. Johansson, B. H. Nilsson, and H. Persson, Collective phenomena in a Penning discharge in a strongly inhomogeneous magnetic mirror field, in *Fifth European Conference on Controlled Fusion and Plasma Physics,* vol. 1, p. 88, Centre d'Etudes Nucléires de Grenoble, Grenoble, France, 1972.

Hultqvist, B., On the interaction between the magnetosphere and ionosphere, in *Solar Terrestrial Physics,* edited by E. R. Dyer, p. 176, D. Reidel, Hingham, Mass., 1972.

Ip, W.-H., and D. A. Mendis, On the interpretation of the observed cometary scintillations, *Astrophys. Space Sci, 35,* L1–L4, 1975.

Ip, W.-H., and D. A. Mendis, The generation of magnetic fields and electric currents in cometary plasma tails, *Icarus, 29,* 147–151, 1976.

Kindel, J. M., and C. F. Kennel, Topside current instabilities, *J. Geophys. Res., 76,* 3055, 1971.

Kivelson, M. G., and C. R. Winge, Field-aligned currents in the Jovian magnetosphere: Pioneer 10 and 11, *Publ. 1476-81*, Inst. of Geophys. and Planet. Phys., Univ. of Calif., Los Angeles, 1975.

Rosenberg, R. L., Unified theory of the interplanetary magnetic field, *Solar Phys., 15*, 72-78, 1970.

Rosenberg, R. L., Heliographic latitude dependence of the IMF dominant polarity in 1972-1973 using Pioneer 10 data, *J. Geophys. Res., 80*, 1339, 1975.

Rosenberg, R. L., and P. J. Coleman, Jr., Heliographic latitude dependence of the dominant polarity of the planetary magnetic field, *J. Geophys. Res., 74*, 5611-5622, 1969.

Rosenberg, R. L., M. G. Kivelson, and P. C. Hedgecock, Heliographic latitude dependence of the dominant polarity of the interplanetary magnetic field by comparison of simultaneous Pioneer 10 and Heos 1, 2 data, *J. Geophys. Res., 82*, 1273-1274, 1977.

Sagdeev, R. Z., Anomalous resistivity in the magnetosphere, in *Physics of the Hot Plasma in the Magnetosphere*, Plenum, New York, 1975.

Schultz, M., Interplanetary sector structure and the heliomagnetic equator, *Astrophys. Space Sci., 24*, 371-383, 1973.

Smith, E. J., B. T. Tsurutani, and R. L. Rosenberg, Pioneer 11 observations of the interplanetary sector structure up to 16° heliographic latitude (abstract), *Eos Trans. AGU, 57*, 997, 1976.

Stangeby, P. C., and J. E. Allen, Current limitation in Mercury vapour discharges, 1, Theory, *J. Phys. A.*, 108-119, 1971.

Swift, D. W., A mechanism for energizing electrons in the magnetosphere, *J. Geophys. Res., 70*, 3061, 1965.

Torvén, S., and M. Babić, Current chopping space charge layers in a low pressure arc plasma, in *Proceedings of the Twelfth International Conference on Phenomena in Ionized Gases*, p. 124, Elsevier, New York, 1975.

Torvén, S., and M. Babić, Current limitation in low pressure Mercury arcs, *Proceedings of the 4th International Conference on Gas Discharges*, p. 323, Institution of Electrical Engineers, London, England, 1976.

Wescott, E. M., H. C. Stenbaeck-Nielsen, T. J. Hallinan, and T. N. Davis, The Skylab barium plasma injection experiments, 2, Evidence for a double layer, *J. Geophys. Res., 81*, 4495-4502, 1976.

Wolf, R. A., Ionosphere-magnetosphere coupling, *Space Sci. Rev., 17*, 537-562, 1975.

Zmuda, A. J., and J. C. Armstrong, The diurnal flow pattern of field-aligned currents, *J. Geophys. Res., 79*, 4611, 1974.

(Received January 14, 1977;
accepted February 17, 1977.)