ELECTRIC CURRENT MODEL
OF MAGNETOSPHERE

Hannes Alfvén

May 1979

Department of Plasma Physics
Royal Institute of Technology
100 44 Stockholm, Sweden
ELECTRIC CURRENT MODEL OF MAGNETOSPHERE

H. Alfven

Royal Institute of Technology, Department of Plasma Physics, S-100 44 Stockholm, Sweden

Abstract

A dualism between the field and the particle approach exists also in plasma physics. A number of phenomena, such as the formation of double layers and the energy transport from one region to another, can be understood only by the particle (electric current) description. Hence a translation of the traditional field description into a particle (electric current) description is essential.

Such a translation has earlier been made for the heliosphere. The purpose of this paper is to outline a similar application to the magnetosphere, focussing on the energy transfer from the solar wind. As a first approximation a magnetic field consisting of a dipole field and homogeneous magnetic field is used whereas in a second approximation the configuration is more realistic.

The solar wind flow through the magnetic field acts as an electric generator. Its power is transferred to the magnetosphere through four main circuits:

1. **The magnetopause circuit**, feeding current to the magnetopause.

2. **The solar wind - auroral circuit**, which produces the sunward plasma drift in the magnetosphere and energizes discharges over the auroral zones where it produces double layers and delivers energy for the auroral display.

3. **The tail circuit**, feeding the neutral sheet current in the magnetotail. By energizing the tail phenomena it also contributes to the sunward drift. This circuit may be disrupted by an explosive double layer. This is the basic mechanism for magnetic substorms.

4. **The front circuit** producing the front current layer ("shock front"). It decelerates the solar wind in front of the magnetopause and deflects it sideways. It also contributes to the magnetopause current.

A fifth circuit is very often energized:

5. **The substorm circuit**. When the tail circuit flares, the current is partly redirected over the auroral zone, flowing in what we call the substorm circuit.
ELECTRIC CURRENT MODEL OF MAGNETOSPHERE

Contents

I. Introduction and general assumptions
   §1 Importance of electric current models
   §2 The particle description
   §3 Different types of electric currents
   §4 Magnetic field model

II Current models
   §5 Zero order approximation: one-particle description
   §6 First order approximation: Plasma flux small
   §7 The three first-approximation circuits
   §8 Phenomena produced by first approximation currents
   §9 Second order approximation: Realistic plasma flux
   §10 Magnetic field changes
   §11 Front (shock front) circuit
   §12 Magnetopause circuit
   §13 Solar wind - aurora circuit
   §14 Tail circuit
   §15 Magnetic substorm circuit
   §16 Third approximation and comparison with observation
   §17 Conclusions
Electric current model of magnetosphere

§1 Importance of electric current models

Traditionally plasma phenomena in space are described in terms of magnetic fields. If by means of Maxwell's first equation such descriptions are translated into current descriptions a deeper understanding is obtained in the following respects: (Alfvén, 1976)

1. The circuit of the current demonstrates the importance of boundary conditions which very often have been forgotten.

2. By directing the attention to the electromotive force driving the current and to the regions of dissipation the energy transfer is more easily understood.

3. Certain types of very important current-produced phenomena, including the formation of double layers, are difficult to understand without accounting for the current explicitly.

As an example, by simply translating the field description of the heliosphere into a current description, it was demonstrated that there must be currents along the solar axis and that the coronal streamers and the polar plumes are likely to be due to filamentary currents.

In this paper we shall make a similar translation of the magnetic field description of the magnetosphere into an electric current description. In principle this is similar to what Heikkila 1974; Rostocker and Boström 1976; Heikkila and Block 1977 and to some extent also to what G. Atkinson 1979 have done.

§2 The particle description

As our main purpose is to describe the transfer of energy from the solar wind to the magnetosphere we confine our analysis to the outer regions of the magnetosphere, including the auroral current regions. Except for the upper ionosphere, these regions are low density regions (Alfvén and Fälthammar, 1963), which means that we can neglect collisions. In contrast the the usual hydro-magnetic description, we shall use exclusively the particle description. Changes in the state of motion of a particle are exclusively caused by the electromagnetic force $e \ddot{\mathbf{r}} + \frac{q}{c} \mathbf{v} \times \mathbf{B}$. 
which acts on it. Hence if a particle stream meets an obstacle, it is deviated only by the force $f_E$ which acts on it and the effect of the obstacle is due to the electric and magnetic fields it produces.

Further, because the Spitzer formula of conductivity is derived under the assumption of a finite mean free path, this is not applicable. Still, if a voltage difference is applied parallel to the magnetic field or along a neutral line, we expect a current to flow, but the voltage-current relation does not obey Ohm's law (Block and Fälthammar, 1976). Double layers and mirror-related voltage drops are more important. Furthermore, a plasma has many different types of instabilities and is normally in an oscillating state. This does not mean that it is turbulent. The sloppy use of the term "turbulent" has caused and is causing much confusion. A spacecraft moving through a plasma often registers rapid fluctuations, but sometimes these are due to the filamentary structure of the plasma, sometimes due to waves of different kinds. However, there is no certain indication that anywhere in space there is very much turbulence in the proper sense of this word. This is very important, among other things because real turbulence produces mixing and there is no certain evidence for a high degree of mixing in space plasmas.

§3 Different types of electric currents

Three main types of electric currents are of importance:

a. Field aligned currents $i_n$ parallel to the B lines.

b. Currents $i_n$ along neutral lines or surfaces $B = 0$.

c. Drift currents $i_l$ perpendicular to B.

(a) In a low density plasma parallel currents do not obey Ohm's law. They may produce double layers, causing large voltage drops and noise (Quon and Wong, 1976; Block, 1978; Carlqvist, 1979; Torvén, 1979; Torvén and Andersson, 1979). Sometimes the double layers explode, which may lead to a disruption of the current. These properties have been demonstrated primarily by experiments but magnetospheric research has now shown that they are of crucial importance for the understanding of space plasmas. They are so complicated that present theories are necessarily semi-empirical. Another important feature is that the currents very often are filamentary. These are good reasons for believing that observed filamentary structures in space are
produced by field aligned currents (Marklund, 1979).

(b) There are a number of theoretical treatments of neutral line (or surface) currents but as these are less well studied in the laboratory we do not know to what extent the theories are valid. In many respects they may be similar to field aligned currents. It is likely that they can form exploding double layers. Experiments by Ohyabu et al, 1974 seem to confirm this (although their interpretation is different).

(c) The perpendicular drift of a charged particle obeys the equation (cf for example Alfvén and Fälthammar, 1963)

\[ \dot{\mathbf{u}} = -\frac{e}{m} \mathbf{E} \times (\dot{\mathbf{E}} + \dot{\mathbf{B}} + \dot{f}_i) \]  

Here \( \dot{f}_E = e\mathbf{E} \), where \( E \) is the electric field. Electric field drifts produce no currents. Magnetic gradient \( \nabla \times B \) produces a force \( \dot{f}_B = \mu \nabla \times B \) (where \( \mu \) is the magnetic moment of the spiralling particle). This produces a magnetic gradient current, e.g. the Störmer ring current. Further, changes in the drift velocity produce inertia drifts associated with

\[ \dot{f}_i = -m \frac{\partial \mathbf{u}}{\partial t} \]  

This drift is important because it transfers kinetic energy into electromagnetic energy (and vice versa). In the first approximation we shall put the plasma temperature equal to zero so that \( \dot{f}_B \) is zero. The drift current \( i \) is given by

\[ i = e n \mathbf{u} = \frac{m e}{B^2} \mathbf{B} \times \frac{\partial \mathbf{u}}{\partial t} \]  

(\( n = \) particle density, \( m = \) particle mass)

§4 Magnetic field model

We shall start with the simplest relevant case: a dipole field \( \mathbf{B}_d = \) dipole moment (representing the terrestrial field) superimposed by a homogeneous interplanetary field \( \mathbf{B}_s \) parallel or antiparallel to the dipole axis, and a uniform solar wind with velocity \( \mathbf{v}_s \) perpendicular to the dipole axis. Hence the magnetosphere is immersed in an electric field \( \mathbf{E}_s = \frac{1}{c} \mathbf{v}_s \times \mathbf{B}_s \) which at large distances from the Earth has the constant value

\[ \mathbf{E}_s = \frac{1}{c} \mathbf{v}_s \times \mathbf{B}_s \]
§5 Zero order approximation: One-particle problem

Our first case is when the plasma flux of the solar wind is so close to zero, that the Debye length is long compared to the size of the magnetic configuration. In this case the motion is a one-particle problem (Alfvén, 1939, 1940, 1955). The interplanetary magnetic field must be northward in order to allow the particles to penetrate into the magnetosphere.

§6 First order approximation: Plasma flux small

In next case we still assume the plasma flux to be so small that the magnetic perturbations are negligible but at the same time the density to be so large that the Debye length is small compared to the typical length. Hence space charge is important with the result that a northward magnetic field produces a space charge cocoon, screening the magnetosphere from the solar wind (Fig. 1). The important case is instead when the interplanetary magnetic field is southward (Fig. 2).

This configuration has the following properties:

a. A neutral line (B=0) is produced in the equatorial plane (z=0) at a distance \( r_n \) from the dipole, with

\[
\frac{r_n}{\lambda} = \left( \frac{\mu_0 \alpha}{B_s} \right)^{1/3}
\]

We define this as the limit of the magnetosphere.

b. For \( z = \infty \) the field lines through the neutral line are located at a circle

\[
r_s = r_n \sqrt{3}.
\]

The homogeneous electric field \( E_s \) in infinity causes a voltage difference

\[
V = 2 r_s E_s
\]

between \( a \) and \( d \) and between \( a' \) and \( d' \) (see Figure 3). The magnetic field configuration transfers this to the magnetosphere, which primarily is subjected to an average electric field

\[
E_m = E_s \sqrt{3}
\]
which has two main effects:

(a) It produces a sunward plasma drift in the equatorial region of the magnetosphere. In order to produce and sustain this a certain current is necessary (Fig. 5).

(b) It produces current along the sunward and the antisunward sectors of the neutral line (see Fig. 3, 4 and 5).

These currents cause an e.m.f. V over the magnetosphere. In a stationary case this will lead to currents along the field lines connecting the magnetosphere with the solar wind. As the field lines which go directly from the polar ionospheres to infinity have very large mirror ratios, currents along these may not be of primary importance. Hence we should expect the currents to flow mainly along the lines of force connecting the neutral line with infinity (fig. 3). When the magnetospheric load produces a voltage drop, the solar wind will get decelerated. This will cause inertia currents in the solar wind, e.g. between a and d, and between a' and d'. These will close the circuit as shown in Fig. 3. In this way solar wind kinetic energy is transferred to the magnetosphere.

§7 The three first-approximation circuits

Depending on how the currents flow in the magnetosphere, we can define three different circuits for transfer of solar wind kinetic energy to the magnetosphere. (There are also electric currents out in the solar wind which do not flow to the magnetosphere.) In all three cases solar wind energy is tapped through inertia currents. Also the transfer by field aligned currents to the neighbourhood of the neutral circle is similar.

A. The magnetopause circuit. The current closes along the sunward part of the neutral line b, c. (For the motivation of the name, see second approximation.)

B. The tail circuit. The current closes through the tail part of the neutral line.

C. Solar wind – aurora circuit. This circuit produces and sustains the sunward plasma drift in the equatorial region of the magnetosphere. As this flow is likely to produce discharges over the auroral region, a large part of the power in this circuit is dissipated as aurora. (Hence the name of the circuit.) See Fig. 5 and 6.
§8 Phenomena produced by first approximation currents

As a summary the first order current system produces the following effects.

A. Changes of the large scale magnetic field.

It is easily seen that the current system produces changes in the large scale magnetic field of the type illustrated in Fig. 4.

B. Magnetospheric drift.

The transfer of the interplanetary electric field to the magnetosphere produces a sunward drift in the region close to the equatorial plane of the type depicted in Fig. 5. (The influence of the plasmasphere is neglected.)

The electric field associated with the drift compensates the applied electric field. Magnetic field lines from the ionosphere may partially shortcircuit the voltage so that currents from the equatorial plane flow to the auroral zone and back again both in the 6\(^{th}\) region, and in the 18\(^{th}\) region in agreement with the Armstrong-Zmuda current system (Armstrong 1974, Zmuda and Armstrong 1974). See Fig. 6. The circuit is closed by ionospheric currents, especially in the auroral zone.

§9 Second order approximation. Realistic plasma flux

We shall now see what happens if we increase the very small solar wind plasma flow to realistic values. Obviously the magnetosphere, including the current system will be considerably deformed. However the topology will probably not change in a decisive way. It seems reasonable that for a next step (which we will call the second approximation) we see what is likely to happen if we scale up the first approximation perturbations very much.

The purpose of the second order approximation is to serve as a basis for a third order approximation, which we will not attempt in this paper.

§10 Magnetic field changes

The large scale magnetic field should be the vector sum of the primary magnetic field and the perturbation field. Fig. 3 shows the result. It is obvious that a comet-like magnetic field is obtained, which is rather similar to the observed field.
The neutral line currents will be transformed into sheet currents by the Dungey effect (Dungey 1961, 1964). At the sunward side of the magnetosphere the line current will spread perpendicular to the equatorial plane, and a sheet will be formed carrying a strong current. We identify this with the magnetopause. It is energized through the magnetopause circuit. In a related way the line current on the back side will spread into a sheet current, but this will be located in the equatorial plane. This should be identified with the tail neutral sheet.

§11 Front_(shock_front)_circuit

In the first approximation the solar wind near the equatorial plane will experience a decreasing magnetic field when it approaches the neutral line. When the magnetopause develops, the magnetic field in front of it will increase. The result is a slowing down of the solar wind drift which is accompanied by an inertia current opposite to the magnetopause current. As long as the magnetic field perturbation deriving from this inertia drift is negligible, the current is distributed over a layer of considerable thickness (see Alfvén, 1954; because of the reversed interplanetary field the sign of the current should be reversed). When the plasma density is so large that the inertia current perturbs the magnetic field very much, the current layer is contracted to a thin sheet. This is identical with the "shock front" derived by the hydro-magnetic approach.

Our model predicts that if the solar wind flow is very low, there should be a distributed current instead of a shock.

In some hydro-magnetic pictures of the "shock front" it is not observed that the current associated with it necessarily must close in some way. In the particle description this is obvious. The force \( i \times B \) in the front layer decelerates the plasma and brings it almost to rest in front of the magnetopause. It must then be accelerated sideways. As in the particle description this can be done only by electromagnetic forces, we conclude that there must flow currents between the front layer and the magnetopause which produces such an acceleration by the \( i \times B \) force. Hence we derive the circuit of Fig. 6 . The front current closes through a current in
the magnetopause, which is added to the current deriving from the magnetopause circuit.

§12 Magnetopause circuit
The magnetopause circuit is basically the same as in the first order approximation: It transfers energy from the solar wind to the magnetopause. However the neutral line current in the first approximation is now changed into a surface current, and it is not quite obvious how this connects with the solar wind currents.

Furthermore, as part of the magnetopause current now is furnished by the front circuit there is a strong coupling with this which may affect its behaviour.

§13 Solar wind - auroral circuit
In the region between the magnetopause and the tail sheet, the sunward drift of the magnetospheric plasma will be basically unchanged.

As soon as the currents to the auroral ionosphere exceeds a certain value, double layers will be formed, but only by currents going upwards from the ionosphere (Lennartsson, 1977). In the double layers an acceleration of charged particles will take place, which are the cause of at least the more brilliant auroras. As we see from Fig. 7 this circuit gives a rather straight-forward transfer of kinetic energy of the solar wind into high energy auroral particles. In other words, the solar wind generator is connected by a high power transmission directly to the auroral consumer of energy.

§14 The tail circuit
The neutral line current in the first approximation is changed into a sheet current. Like in the magnetosphere circuit, it is not very clear how its connections with the solar wind currents are modified.

The current flows through the neutral sheet in the tail producing the characteristic tail structure. The circuit transfers solar wind energy into inductive energy of this circuit, manifesting itself as a change in the tail magnetic field. When the neutral sheet current exceeds a critical value an explosive double layer is formed, which is likely to be the cause of a magnetic substorm:
The tail current disrupts (at least partially) and the current is redirected over the auroral zone. This is likely to be the basic mechanism of a magnetic substorm.

This shows that the tail circuit transfer is a very important part of the total energy delivered by the solar wind to the magnetosphere.

§15 The magnetic substorm circuit
This has been derived by Boström and is depicted in Fig. 8.

§16 Third approximation and comparison with observation
When the first and second approximations we worked out in details, these should serve as a platform for a third approximation, which hopefully should give a good picture of the observational reality. Among the many difficult problems which will turn up are the following.

It is not certain that the solar wind-aurora circuit is the most important source of energy for the aurora. It is quite possible that a large, perhaps the largest, source of energy for the aurora derives from the tail circuit, as suggested by Boström (1974). Block (1979) has suggested an interesting alternative circuit. As pointed out especially by Peikkila and Block (1977) there is a plasma layer just inside the magnetopause which moves along the magnetopause surface. Its direction is the same as that of the solar wind just outside the magnetopause. This might be similar to sideway flow and its origin may be similar: The braking of the sunward flow before it reaches the magnetopause should produce an effect of the same kind as the solar wind does in front of the magnetopause. However also other explanations should be considered (Block, 1979).

§17 Conclusions
The aim of this paper is to outline the general approach to a current model of the magnetosphere. It is concluded that this approach may facilitate the understanding of several magnetospheric phenomena, especially the mechanism of how solar wind energy is transferred to the magnetosphere.
Acknowledgement. I have profited much from discussions with many colleagues at this Institute, especially Drs L. Block, C.-G. Fält-hammar, L. Lindberg and S. Torvén. I have also had a good collaboration with colleagues at the UCSD, La Jolla, especially Drs C. McIllwain, A. Mendis and E. Whipple.
Referenser


Block, L.P., Private communication, 1979.


Heikkila, W.J., Outline of a Magnetospheric Theory, J. Geophys. Res. 79, 2496, 1974

Heikkila, W.J. and Block, L.P., Review of Magnetospheric Boundary Layer Phenomena and Relations to Current Theories, Geophysica, 14:2, 165, 1977


Figure captions

Fig. 1 Northward interplanetary field.
The magnetosphere is screened from solar wind
electric field $E_s$.

Fig. 2 Southward interplanetary field.
The magnetosphere is primarily embedded in an
electric field $E = E_s \sqrt{3}$.

Fig. 3 Current system seen from sun.
The solar wind electric field produces a voltage
difference between the field lines $aba'$ and $cd'$,
which produces a current along the sunward and the
antisolar parts of the neutral line $bc$. It also
causes a current over the magnetosphere.

Fig. 4 Current system seen from dusk side.
(Also showing the plasma flow.) The field aligned
currents to the $6^h$ side and from the $18^h$ side of
the neutral line are closed through the sunward
part of the neutral line (resulting in the forma-
tion of the magnetopause) and the antisolar part
(resulting in the tail neutral sheet).

Fig. 5 Current system seen from north.
Field aligned currents from the solar wind flow in
on the $6^h$ side and out on the $18^h$ side. They close
through the magnetopause current on the $12^h$ side and
through the tail current on the $24^h$ side. Moreover,
the electric field imposed on the magnetosphere causes
a sunward drift, and in order to accelerate and sustain
this currents across the magnetosphere.

Fig. 6 Front circuit
The front (shock front) current decelerates the
solar wind in front of the magnetosphere. Currents
connecting the front current with the magnetosphere
accelerate the plasma sideways and later antisolari-
wards around the magnetopause. The currents close
through the magnetopause.
Fig. 7 Solar wind - aurora circuit. (Central part of Fig. 3.) Currents from the solar wind connect through the magnetosphere in order to accelerate and sustain the sunward plasma flow. Part of this current may be short-circuited along the magnetized field lines from the auroral zone, producing the Armstrong-Zmuda current system. (The dotted line near the Earth is meant to indicate that the current does not connect to the equator but is closed on both sides of the Earth.)

Fig. 8 Magnetic substorm circuit
Fig. 1

Northward field.
Fig. 2
Southward field.
Fig. 3
Current system, seen from sun.
Magnetic field from current system.

Vector sum of initial field and current produced field.

Typical resultant magnetic field line.

**Fig. 4**

Seen from dusk side.
Fig. 5
Solar wind auroral circuit from north.
Fig. 7
Auroral current system, from sun.
(Detail from fig. 3)
Fig. 6

Front circuit, from north.
Equivalent circuit for the substorm current system. At the substorm onset the resistance of the neutral sheet increases and the tail current is redirected to the ionosphere.

Fig. 8
TRITA-EPP-79-09

Royal Institute of Technology, Department of Plasma Physics, S-100 44 Stockholm, Sweden

ELECTRIC CURRENT MODEL OF MAGNETOSPHERE

H. Alfvén

May 1979, 22 pp. incl. ill., in English

A dualism between the field and the particle approach exists also in plasma physics. A number of phenomena, such as the formation of double layers and the energy transport from one region to another, can be understood only by the particle (electric current) description. Hence a translation of the traditional field description into a particle (electric current) description is essential.

Such a translation has earlier been made for the heliosphere. The purpose of this paper is to outline a similar application to the magnetosphere, focussing on the energy transfer from the solar wind. As a first approximation a magnetic field consisting of a dipole field and homogeneous magnetic field is used whereas in a second approximation the configuration is more realistic.

The solar wind flow through the magnetic field acts as an electric generator. Its power is transferred to the magnetosphere through four main circuits:

1. The magnetopause circuit, feeding current to the magnetopause.

2. The solar wind - auroral circuit, which produces the sunward plasma drift in the magnetosphere and energizes discharges over the auroral zones where it produces double layers and delivers energy for the auroral display.

3. The tail circuit, feeding the neutral sheet current in the magnetotail. By energizing the tail phenomena it also contributes to the sunward drift. This circuit may be disrupted by an explosive double layer. This is the basic mechanism for magnetic substorms.

4. The front circuit producing the front current layer ("shock front"). It decelerates the solar wind in front of the magnetopause and deflects it sideways. It also contributes to the magnetopause current.

A fifth circuit is very often energized:

5. The substorm circuit. When the tail circuit flares, the current is partly redirected over the auroral zone, flowing in what we call the substorm circuit.

Key words: Magnetosphere, magnetopause, electric current system, circuit theory, transfer of energy.