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MAGNETOSPHERIC CURRENTS

A description of the earth's magnetosphere and associated currents and a review of the past and present studies of magnetospheric currents are provided in this article.

When viewed from outer space, the earth's magnetic field does not resemble a simple dipole but is severely distorted into a comet-shaped configuration by the continuous flow of solar wind plasma. A complicated system of currents flowing within this distorted magnetic field configuration is called the "magnetosphere." The magnetospheric system includes (a) a large-scale current system that flows across the geomagnetic field lines on the dayside, (b) currents that flow in the "tail," (c) Birkeland currents that flow along geomagnetic field lines into and away from the auroral regions near the North and South Poles, (d) the ring current that flows at high altitudes around the equator of the earth, and (e) a complex system of currents that flow completely within the layers of the ionosphere, the earth's ionized atmosphere.

HISTORICAL INTRODUCTION

The first systematic and scientific study of the earth's magnetic field was conducted by William Gilbert, who published his findings in *De Magnete* in 1600 (see the cover of the *Johns Hopkins APL Technical Digest*, Vol. 1, No. 3, 1980). This treatise was published nearly a century before Newton's *Philosophiae Naturalis Principia Mathematica* (1687). The fact that the magnetic field is not absolutely steady but is continually changing and may experience violent changes was noted by several scientists; according to Chapman and Bartels,[1] the connection between the aurora and these "magnetic storms" was first suggested by Halley in 1716. Later, in the same century, the Swedish physicist Celsius and his student Hiorter made similar discoveries. In a paper published at the Swedish Academy of Sciences in 1777, Hiorter reported the following:

> But who could have imagined that there was any connection between the aurora and the magnetic needle, and that the aurora, when passing over the zenith to the south or accumulating near the western or eastern horizon, would cause a considerable perturbation of the magnetic needle amounting to several degrees within a few minutes? The first time I saw an aurora in the south and simultaneously observed the greater variation of the magnetic needle was on March 1, 1741 in the evening, after having several times noticed the irregular behavior of the needle but not seen the aurora owing to overcast sky. When I told the late professor [Celsius] of this he said that he had also observed a similar perturbation of the needle under the same circumstances, but that he had not mentioned it because he wished to see if I (such were his words) should happen to have the same idea.[2]

One wonders how fair Celsius was being to his student!

In 1838, Gauss recognized that the magnetic field measured on the surface of the earth does not originate entirely within the earth, but that some of it may be of external origin due to currents flowing somewhere above the surface. Following the discovery of cathode rays, Gauss even suggested the possibility of "electric currents . . . sent out from the sun." In his famous *Allgemeine Theorie des Erdmagnetismus*,[2] Gauss writes:

> The hypothesis that empty space can admit currents of electricity has of course far-reaching consequences, in particular for cosmic phenomena. The fate of most of the theories of cosmic physics founded on experiments can hardly encourage further attempts. I may suggest, however, that certain terrestrial phenomena of electric or magnetic nature, which — on account of the coincidence of their periods or single appearances with solar phenomena — were tentatively attributed to statical influence, magnetic induction and so on, from the sun, may perhaps be better explained by the action of electric currents, which are sent out from the sun into space. In fact the experiments show, through successive elimination of the ponderable matter, that no limit for the extension of what we call cathode rays exists, and it may be conceivable that the sun besides light also sends out into space electric rays.

In 1882, Balfour Stewart suggested that currents flowing at high altitudes where the atmosphere may be ionized are the source of the observed day-to-night variation in the earth's surface magnetic field at midlatitude. Following Marconi's 1901 demonstration of trans-Atlantic radio communication, A. E. Kennelly and Oliver Heaviside also suggested the possibility of a layer of ionized gas (now referred to as "plasma") in the upper atmosphere. A series of radio propagation experiments performed in the early 1920's simultaneously by Edward Appleton in Great Britain and by Merle A. Tuve and Gregory Breit of the Carnegie Institution in Washington, D.C., confirmed the presence of the "ionosphere." Appleton later was knighted and won the Nobel prize for his work on the ionosphere. Tuve became the first director of the Applied Physics Laboratory. Similar radio propagation experiments were conducted by C. K. Jen at about the same time.[3]

Inspired by his famous terella experiments at the end of the 19th century and by his extensive studies of geomagnetic data recorded during magnetic storms, Kristian Birkeland also suggested that the aurora was due to cathode rays or similar electric corpuscular rays sent out from the sun and deflected to the polar regions of the earth by the geomagnetic field. Birkeland recognized that the geomagnetic disturbances recorded on the earth's surface below the auroral region were due to intense currents flowing horizontally above. These are referred to today as auroral electrojets and are Hall currents resulting from large-scale electric fields directed perpendicular to the geomagnetic field. E. O. Hall received the second Ph.D. degree awarded by the Physics Department of The Johns Hopkins University in 1880 for his discovery, now referred to as the "Hall Effect."[4] In Birkeland's words:

> We consider it to be beyond doubt that the powerful storms in the northern regions, both those of long duration, and the short, well-defined storms that we have called elementary, are due to the action of electric currents above the surface of the Earth near the auroral zone. These currents, as far as the elementary storms are concerned at any rate, act, in the districts in which the perturbation is most powerful, as almost linear currents, that for a considerable distance are approximately horizontal.

He went on to compute the current strength to vary between 5×10^5 and 1×10^6 amperes and determined the altitude of these currents to be above 100 kilometers. Present values are 3×10^5 amperes for the westward electrojet, which occurs between 100 and 120 kilometers altitude,[5] and 2×10^6 to 5×10^6 amperes for the total system of field-aligned currents.[6]

Birkeland was concerned, however, about these horizontal currents, as is reflected in his writing:

> With regard to the further course of the current, there are two possibilities that may be considered. (1) The entire current-system belongs to the Earth. The current-lines are really lines where the current flows upon the Earth's surface, or rather at some height above it. (2) The current is maintained by a constant supply of electricity from without. The current will consist principally of vertical portions. At some distance from the Earth's surface, the current from above will turn off and continue for some time in an almost horizontal direction, and then either once more leave the Earth, or become partially absorbed by its atmosphere.

Birkeland apparently favored the second suggestion from his terrella experiments and Störmer's calculations, and proposed the field-aligned current system, reproduced here as Fig. 1. But his two suggestions became the source of a controversy concerning current systems that continued for a quarter of a century. Birkeland's first suggestion, concerning the containment of the current system within the earth's vicinity, was vigorously promoted by S. Chapman and his colleagues, and the model with the field-aligned currents was developed and advanced by H. Alfvén. Figure 2 shows Alfvén's diagram of those currents responsible for the aurora.

However, the reluctance to accept the concept of Birkeland's field-aligned currents is illustrated by the following quotations from papers by Chapman: "The question whether or not the currents flow wholly in the atmosphere is discussed, and it is concluded, though not decisively, that the evidence favors this view."[10] The objections became stronger: "The electric current-system of Birkeland gives rise to a disturbance-field shown to be inconsistent with observation in several important respects."[11] "The apparently unshakable hold on Birkeland's mind of his basic but invalid concept of intense electron beams, mingled error inextricably with truth in the presentation of ideas and experiments on auroras and magnetic storms."[12]

The existence of field-aligned currents was disputed because it is not possible to distinguish unambiguously between current systems that are field-aligned and those that are completely ionospheric from a study of surface magnetic field measurements only.[13] The first satellite measurements of Birkeland currents were made by A. J. Zmuda *et al.*[14,15] with a magnetometer on board the polar orbiting satellite 1963-38C at approximately 1100 kilometers altitude. The magnetic disturbances observed by Zmuda *et al.* were initially interpreted as hydromagnetic waves.

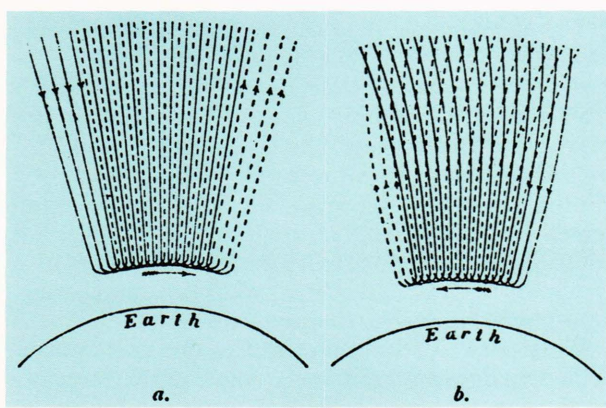

Figure 1 — The system of field-aligned currents as published by Birkeland in 1908.[7] In consideration of the fact that auroral phenomena were often directly associated with solar activity, Birkeland believed that the horizontal currents had to couple to vertical currents flowing along geomagnetic field lines that, in turn, ultimately were connected to the sun.

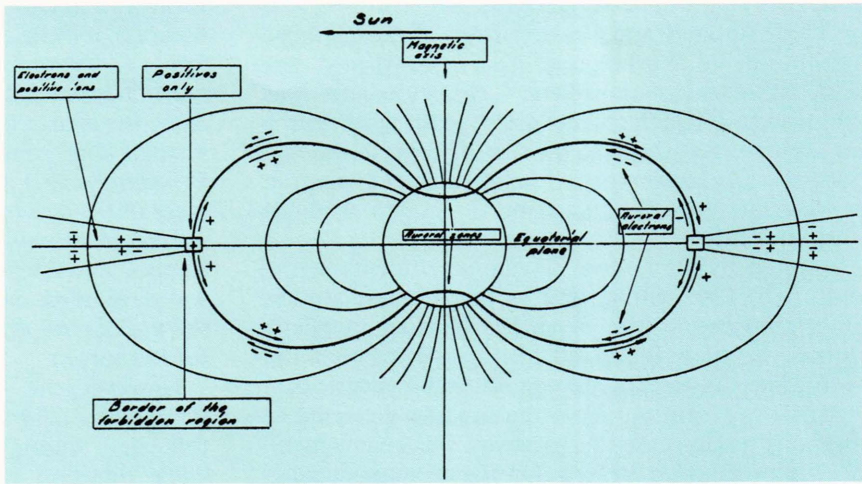

Figure 2 — The complete system of field-aligned currents proposed by Alfvén in 1939.[8,9] He proposed that the interaction of solar wind plasma with the earth's magnetic field produced regions of positive and negative space charge (indicated in the figure) that were neutralized by currents flowing along geomagnetic field lines into and away from the auroral zones.

But it was soon realized that their latitudinal extent was too small for waves of the appropriate wavelength, and they were interpreted as being due to field-aligned or Birkeland currents.[16] Many observations of Birkeland currents have been reported during the last few years by virtue of their associated magnetic variations detected by satellite-borne magnetometers, including the APL-built TRIAD, MAGSAT, and HILAT spacecraft.

The importance of the Birkeland currents to the coupling between the magnetosphere and the auroral atmosphere and ionosphere is demonstrated by their total intensity, which ranges between 10^6 and 10^7 amperes, and by the energy that they dissipate in the upper atmosphere, which can exceed by a considerable factor the energy deposition associated with the dramatic visual auroral forms. The three-dimensional current system that flows throughout the magnetosphere and auroral ionosphere is described in the following section.

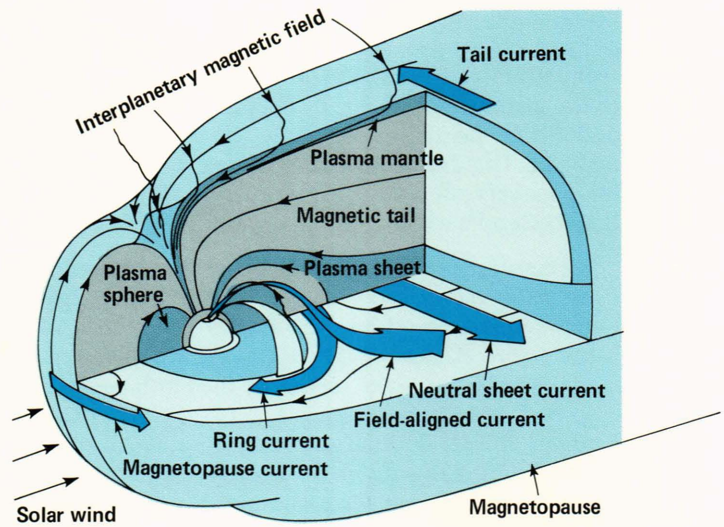

Figure 3 — The configuration of the earth's dipole magnetic field distorted into the comet-like shape called the magnetosphere. The various current systems that flow in this complicated plasma laboratory are labeled. The interplanetary magnetic field is the magnetic field of the sun, which has a modulating effect on the processes that occur within the magnetosphere.

THE MAGNETOSPHERE

The geomagnetic field can be thought of as being produced by a huge bar magnet embedded in the earth, with the axis of the magnet tilted away slightly from the earth's rotational axis. The poles of this magnet are located near Thule, Greenland, and Vostok, Antarctica (a USSR research station). To a good approximation, the geomagnetic field can be represented by a simple dipole, but there is a significant contribution from nondipole components and from a system of complicated currents that flow in the magnetospheric regions surrounding the earth.

When viewed from outer space, the earth's magnetic field does not resemble a simple dipole but is severely distorted into a comet-shaped configuration (depicted in Fig. 3) by the continuous flow of plasma (the solar wind) from the sun. This distortion requires the existence of a complicated set of currents flowing within the distorted magnetic field configuration called the magnetosphere. For example, the compression of the geomagnetic field by the solar wind plasma on the dayside of the earth must give rise to a large-scale current flowing across the geomagnetic field lines, called the Chapman-Ferraro or magnetopause current. The magnetospheric system also includes large-scale currents that flow in the tail, Birkeland currents that flow along geomagnetic field lines into and away from the two auroral regions, the ring current that flows at high altitudes around the equator of the earth, and a complex system of currents that flow completely within the layers of the ionosphere. The intensities of these various currents reach millions of amperes and are closely related to solar activity. They produce magnetic fields that vary with time, with time scales ranging from a few seconds (micropulsations) to 11 years (corresponding to the solar cycle).

THE INTERPLANETARY MAGNETIC FIELD

The rotating sun, coupled with its continual radial ejection of plasma, twists its magnetic field (which is referred to as the interplanetary magnetic field) into a classical Archimedean spiral, as depicted in Fig. 4. Spacecraft measurements so far have been restricted to the neighborhood of the ecliptic plane. (The International Solar Polar Mission, the first spacecraft to travel over the pole of the sun, will be launched in 1986 and will carry an APL-built particle experiment.) Measurements to date have determined that the interplanetary magnetic field is directed toward the sun in certain regions of the sun and away from the sun in other regions. These regions are separated by a very sharp boundary, which Alfvén has suggested is a current layer. Alfvén further suggested that the current sheet of the sun extends into the interplanetary medium from the solar equator and that this sheet develops "ripples" (as depicted in Fig. 5). In this situation, the earth finds itself sometimes in a region where the field has a strong northward component and sometimes where it has a strong southward component. The orientation of the interplanetary magnetic field with respect to the geomagnetic field has a profound influence on the processes that are involved in the transfer of plasma and energy from the solar wind to the earth and ultimately to a variety of auroral phenomena.

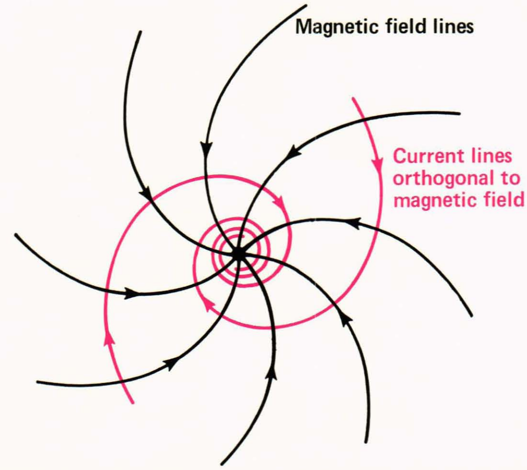

Figure 4 — Magnetic field lines of the sun (the interplanetary magnetic field), which are bent into Archimedean spirals owing to the combination of the rotation of the sun and the radial emission of plasma (which carries the "frozen-in" magnetic field). This is a view over the north pole of the sun looking downward at the field lines slightly above the sun's equatorial plane. Close below the equatorial plane, the field lines have the same geometry but opposite direction. The shapes of the associated current lines are also shown.[17]

THE RELATIONSHIP BETWEEN THE INTERPLANETARY MAGNETIC FIELD AND THE GEOMAGNETIC FIELD

One of the most interesting, but as yet unsolved, problems of space plasma physics involves the effect of the variable orientation of the interplanetary magnetic field on the topology and stability of the magnetosphere's boundary. Considerable evidence exists from spacecraft measurements that conditions inside the magnetosphere are more active (i.e., more frequent occurrence of auroras and geomagnetic storms) when the field is directed southward than when it points northward. The magnetic field topology corresponding to these two conditions is shown in Fig. 6. When the interplanetary magnetic field is directed southward, the field lines are antiparallel to

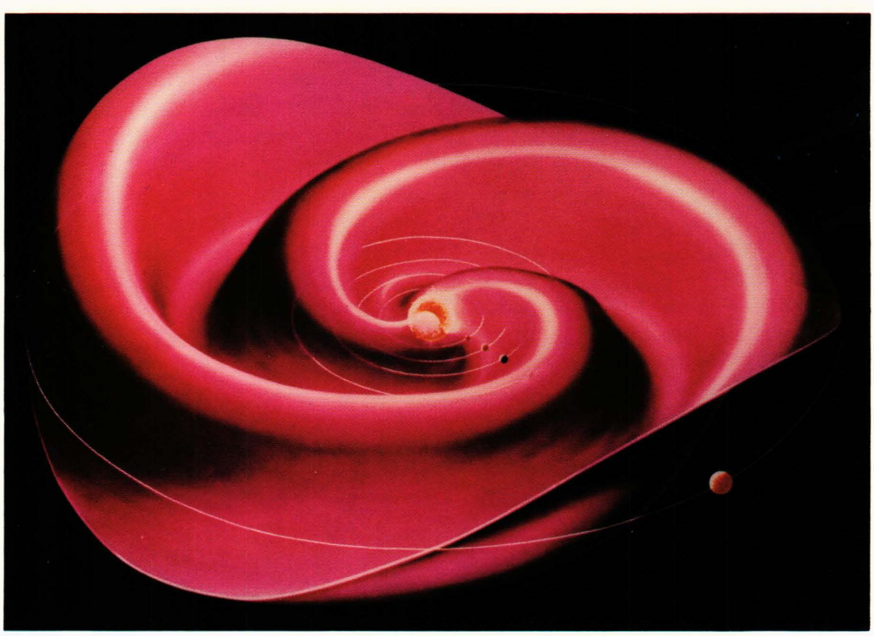

Figure 5 — The solar current sheet in the equatorial plane. Alfvén has proposed that the sheet develops ripples like the skirt of a ballerina. As this system rotates, the earth finds itself in different regions so that the interplanetary magnetic field can assume a variety of orientations, e.g., directed toward or away from the sun, and northward or southward.

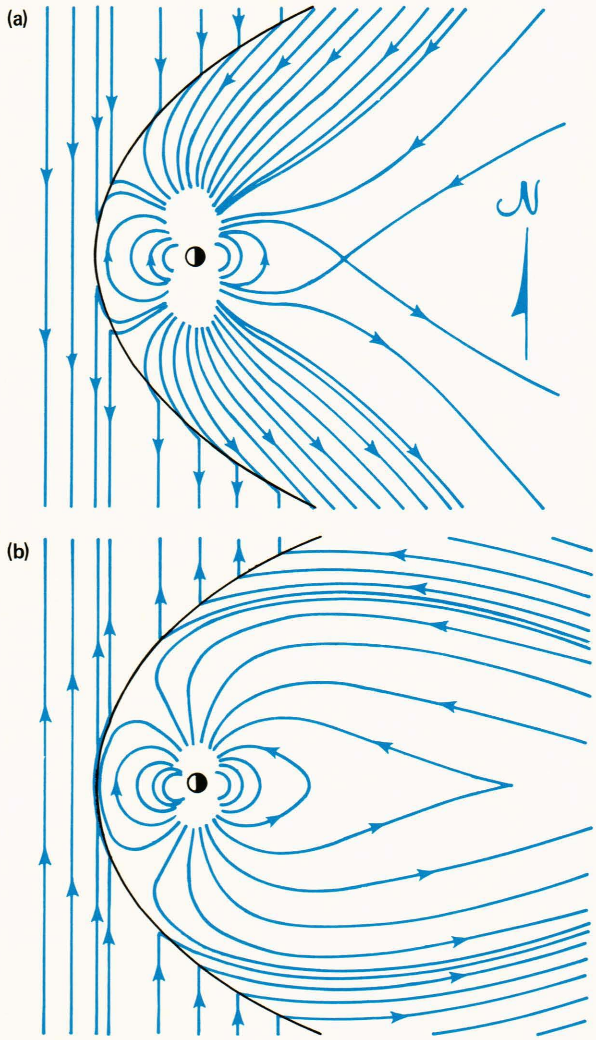

Figure 6 — Magnetic field topology for conditions with the interplanetary field directed southward in panel (a) and northward in panel (b). When the interplanetary magnetic field is directed southward, a magnetic "neutral" region is thought to occur on the dayside geomagnetic field lines where the process of reconnection may allow the free transport of solar wind plasma into the magnetosphere. When the field is northward, it has been suggested that the magnetosphere may be completely insulated from the solar wind, but there is mounting evidence that reconnection may occur on the geomagnetic field lines in the tail.

the geomagnetic field lines at the front of the magnetosphere (as shown in Fig. 6a), forming "neutral" points. In this situation it has been suggested that a process called "reconnection" occurs in which the solar wind plasma may have free access, and even be accelerated, into the magnetosphere. When the interplanetary magnetic field is directed northward (as shown in Fig. 6b), the field lines and dayside geomagnetic field lines are parallel, and the solar wind plasma is effectively "shut off" on the dayside of the earth. There is mounting evidence that reconnection may occur on the tail geomagnetic field lines, in which case the polar cap and auroral phenomena are quite different. For example, the visual auroral forms and associated energetic particle precipitation and currents are found at much higher geomagnetic latitudes — close to the geomagnetic pole. The orientation and shapes of the auroral forms when the field is northward directed are also quite different in comparison to periods when the field is southward. The relationship of the orientation of the interplanetary magnetic field and the geomagnetic field is very complex and is the key element in a variety of magnetospheric phenomena. There have even been suggestions that the north-south orientation of the magnetic field may have a relationship with meteorological phenomena.[18]

CONVECTIVE FLOW

The viscous-like interaction between the solar wind and the magnetosphere causes a large-scale "convection motion" of plasma in the magnetosphere, as depicted in Fig. 7a. This flow pattern maps down to the earth's polar ionosphere, as shown in Fig. 7b. The flow pattern consists of a two-cell pattern, with plasma flowing away from the sun in the polar cap of the earth and toward the sun in the auroral zones. This pattern is similar to that produced in a teacup when one blows gently across the surface of the tea. The relatively stable two-cell pattern can exist only during periods when the magnetic field is directed southward and reconnection presumably occurs on the dayside of the magnetosphere. This convective flow pattern is severely distorted, even breaking into multiple cells when the magnetic field is northward.

The antisunward plasma flow in the earth's polar cap produces an electric field directed from dawn to dusk, as shown in Fig. 8 as E_{PC}. The sunward flow in the auroral zones produces electric fields in the opposite direction (labeled E_{AZ} in Fig. 8). The auroral zone electric field drives Hall currents in a direction opposite to the convective flow (i.e., in the sunward direction, labeled I_H). Typical convective flow speeds of 1 kilometer per second will produce polar cap electric fields of 50 millivolts per meter and potential drops of 10 kilovolts across a 200 kilometer wide auroral zone. The potential drops can reach 50 to 100 kilovolts during disturbed periods. As mentioned earlier, the Hall currents associated with these electric fields are referred to as the "auroral electrojet" current system, which can reach intensities of 3×10^5 amperes. The Hall current on the dawn side is referred to as the "westward electrojet" and on the dusk side as the "eastward electrojet." This system of currents is mainly responsible for the surface magnetic disturbances historically observed during auroral displays.

FIELD-ALIGNED BIRKELAND CURRENTS

Building upon Zmuda's confirmation of the presence of field-aligned Birkeland currents, data acquired by the APL-built TRIAD and MAGSAT spacecraft have been used to study the detailed characteristics of these currents. Their intensities, flow di-

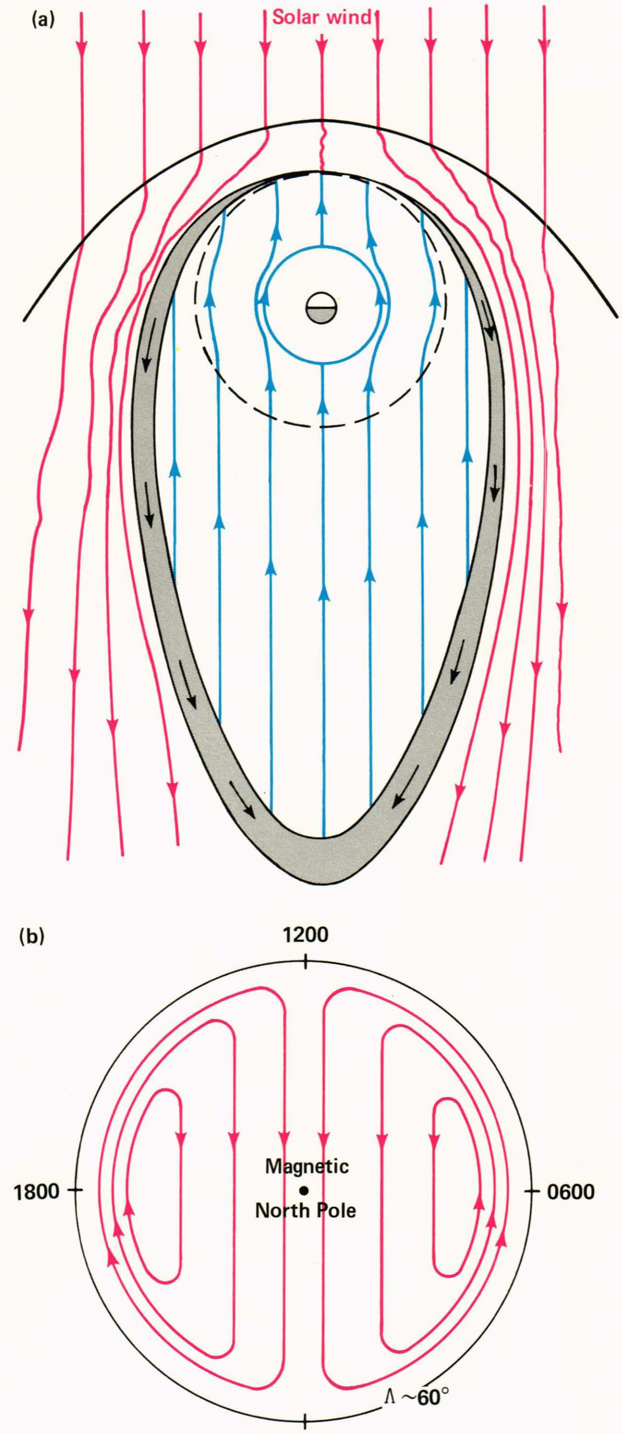

Figure 7 — (a) A sketch of the equatorial section of the earth's magnetosphere looking from about the North Pole. Streamlines of the solar wind are shown on the exterior; the internal streamlines refer to the circulation that, it is proposed, is set up by viscous interaction between the solar wind and the surface of the magnetosphere. (b) A sketch of the circulation at ionospheric levels in the north polar cap corresponding to the internal circulation in the magnetosphere shown in Fig. 7a.

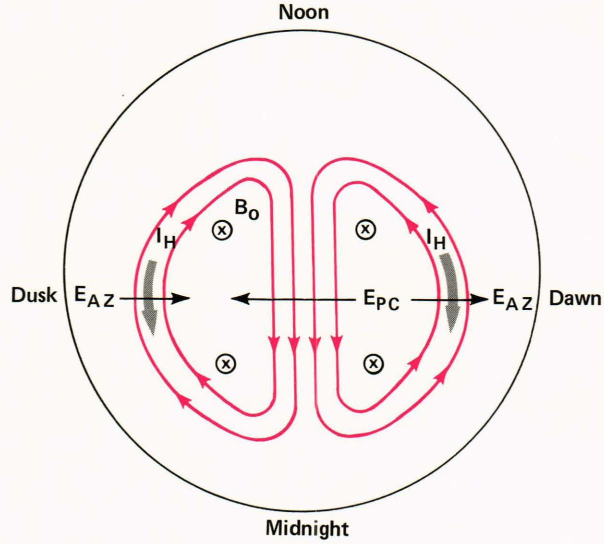

Figure 8 — A schematic view of the north polar region of the earth. The two-cell convective flow pattern is denoted by the closed solid lines with arrows directed toward midnight (i.e., antisunward) in the polar cap and directed toward noon (sunward) in the auroral regions. The electric fields produced by this convective flow through the earth's magnetic field (B_0) are denoted by E_{PC} in the polar cap and E_{AZ} in the auroral zones. The auroral Hall currents are labeled I_H.

rections, and locations are determined from the transverse magnetic disturbances they produce, which can be measured with satellite-borne magnetometers (see, for example, the special MAGSAT issue of the *Johns Hopkins APL Technical Digest,* Vol. 1, No. 3, 1980).

Large-scale Birkeland currents are concentrated in two large areas that encircle the geomagnetic pole.[19-22] Figure 9 is a summary of the average spatial distribution in the northern high-latitude region determined from 493 TRIAD passes during weakly disturbed conditions and 366 TRIAD passes during active periods.[6] The Birkeland current flow regions have been arbitrarily designated by Iijima and Potemra[21,22] as Region 1 located at the poleward side and Region 2 located at the equatorward side. The Region 1 Birkeland currents flow into the ionosphere in the morning sector and away from the ionosphere in the evening sector; the Region 2 currents flow in the opposite direction at any given local time. A three-region flow pattern of Birkeland currents exists in the 2200 to 2400 magnetic local time sector (sometimes referred to as the "Harang discontinuity region") that may be thought of as an overlapping of the two-region flow patterns usually observed in the surrounding magnetic local time sectors. The basic flow pattern of Birkeland currents is the same during geomagnetically inactive and active periods, as shown in Fig. 9, although the regions widen and shift to lower latitudes during disturbed periods. Complicated small-scale structures are superimposed upon the large-scale Birkeland current features, especially near the high-latitude noon region associated with the cusp and on the nightside during substorm events (see Ref. 13 for details).

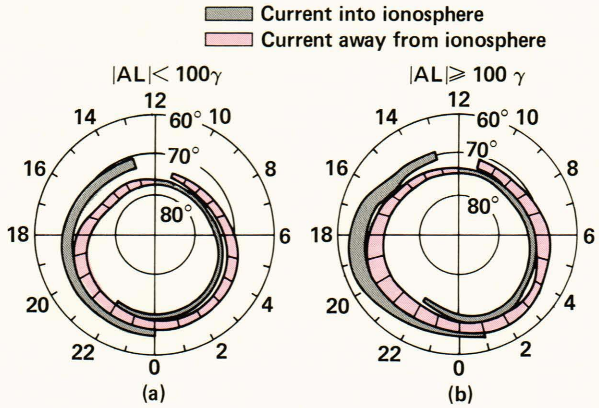

Figure 9 — A summary of the distribution and flow directions of large-scale Birkeland currents during (a) weakly disturbed conditions and (b) active periods (see Ref. 6, Fig. 13). These patterns were determined from the analysis of magnetic field data acquired by the U.S. Navy/APL TRIAD satellite during hundreds of orbits over several years.

A new technique for the study of the Birkeland current distributions has been made possible by the unique combination of a sun-synchronous orbit and the continuous vector magnetic field data provided by the MAGSAT spacecraft. In a half day, the orbits of MAGSAT covered the north polar region from 75° (eccentric dipole latitude) at noon to 85° at midnight and the south polar region from about 70° at midnight to 85° at noon. When the data from both hemispheres were combined, MAGSAT provided a "global image" of the locations, flow directions, and intensities of Birkeland currents in the entire auroral zone for 12 hours. Current densities were computed from the magnetic disturbances measured by MAGSAT; these values were color-coded for intensity and flow direction and plotted on an eccentric magnetic dipole latitude-magnetic local time circular plot for each consecutive orbit. This was done for MAGSAT data acquired on December 23, 1979, when the interplanetary magnetic field component was steady and northward, and on March 21, 1980, when it was southward. The plots are shown in Fig. 10. These color plots are 24-hour "snapshots" of the Birkeland current distributions. During the day, when the field was southward, the image of the current distributions (Fig. 10a) displays the familiar oval pattern of Region 1 and Region 2 currents.[18] During the day, when the field was northward (Fig. 10b), the pattern of currents is almost completely confined to latitudes above 75°, and their flow pattern is very complicated. These global images of Birkeland currents support previous analyses that concluded that the three-dimensional Birkeland ionosphere current system (along with such associated phenomena as visual auroral forms, particle precipitation, and convective flow) is intimately related to the orientation of the interplanetary magnetic field component and moves to polar cap latitudes during periods of northward field.

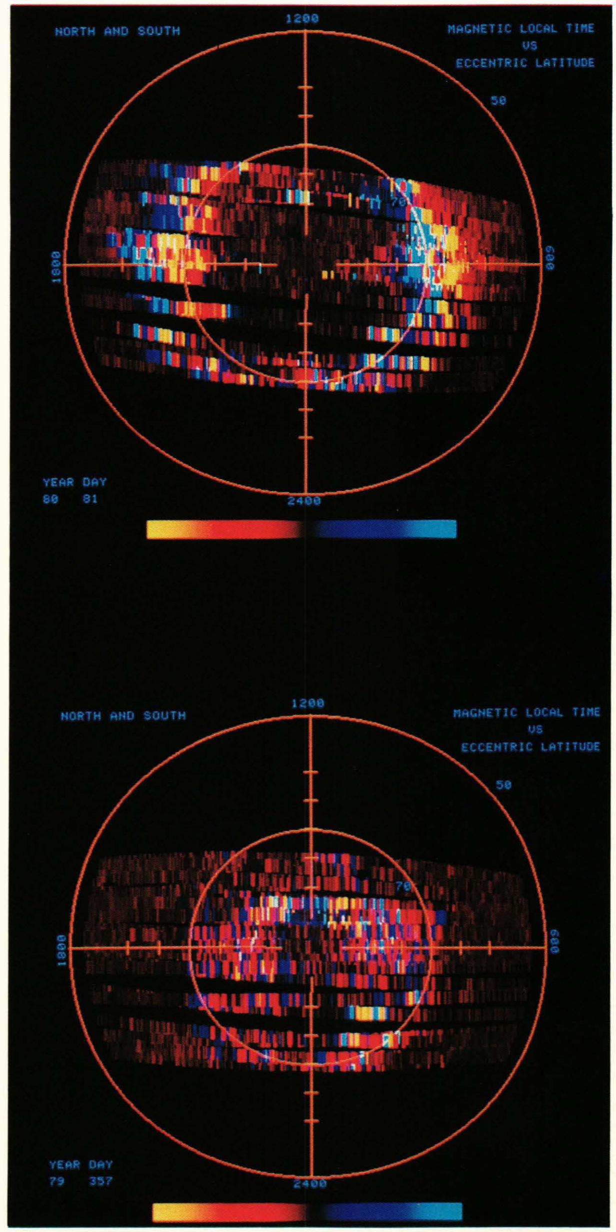

Figure 10 — Global images of field-aligned currents determined from the MAGSAT satellite magnetic field observations. The current values computed from the observed magnetic disturbances were color-coded for intensity and flow direction and plotted on a polar plot for each consecutive orbit throughout the day. Figure 10a shows that during a day when the interplanetary magnetic field was directed southward, the image of the current distributions displays the familiar oval pattern of Region 1 and Region 2 currents (see Fig. 9). During a day when the field was northward, the pattern of currents is almost completely confined to latitudes above 75°, and their flow pattern is very complicated, as shown in Fig. 10b. These observations confirm the intimate relationship between auroral phenomena and the orientation of the magnetic field. (From Ref. 23.)

BIRKELAND CURRENTS AND AURORAL EMISSIONS

The charged particles that carry the field-aligned Birkeland currents may excite the auroral atmosphere and produce emissions that may be detected on the ground or in outer space with satellites. Downward flowing energetic electrons produce auroral emissions and also carry an upward flowing Birkeland current. The APL-built HILAT satellite (launched on June 27, 1983) carries a variety of instruments to study aurora phenomena.[24] Included are an ultraviolet imager called the Auroral Ionospheric Mapper, which obtained the first auroral images in the daylit auroral zone, and a magnetometer experiment to study Birkeland currents. Figure 11 shows the image at 1356 Å recorded by the Air Force Geophysics Laboratory/APL Auroral Ionospheric Mapper on July 17, 1983, with the in situ magnetic field observations superimposed on the right. The spacecraft is traveling in complete daylight from high to low latitudes over the dawn sector near 0500 magnetic local time. The magnetometer trace along the right side of Fig. 11 shows a large perturbation extending from 63° to 69° magnetic latitude, which is due to a large-scale pair of Birkeland currents. A current of 1.1 microamperes per square meter flows away from the ionosphere in the region of the intense UV auroral arc. The downward flowing electrons producing the UV emissions carry the upward flowing current (referred to as the Region 2 system). Poleward of this current is a downward flowing Birkeland current of 0.7 microampere per square meter, which is the corresponding Region 1 system (see Fig. 9).

SOME REMAINING QUESTIONS

Large-scale currents that flow into and away from the earth's auroral and polar regions comprise a permanent element in the circuit connecting interplanetary space and the lower ionosphere. The Birkeland currents are associated with a wide variety of auroral phenomena including visual and radar forms, ionosphere currents, and ionospheric plasma instabilities. An International Conference on Magnetospheric Currents was held in Irvington, Va., in April 1983, in which over 90 registrants from four continents parti-

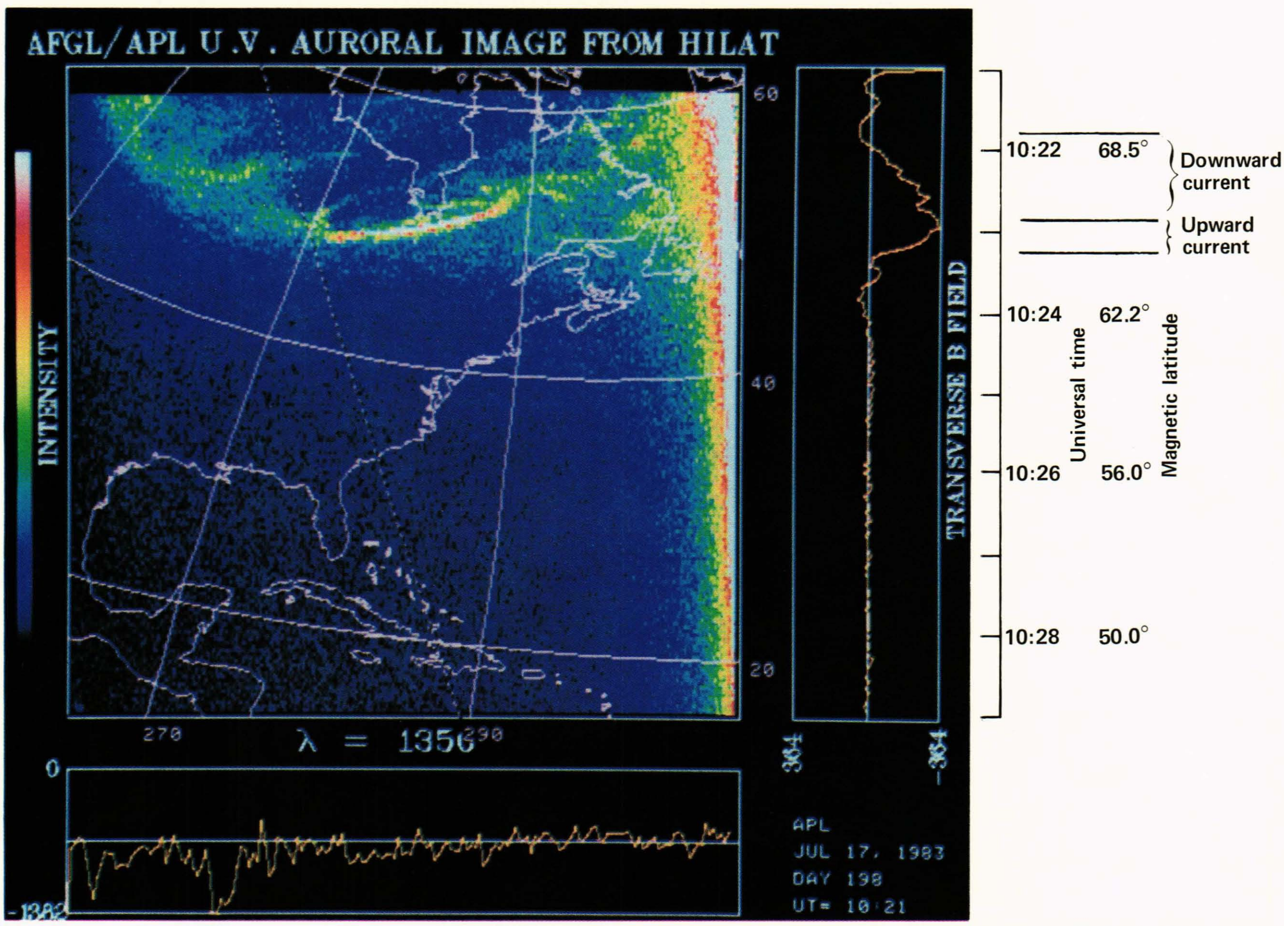

Figure 11 — A bright vacuum ultraviolet (1356 Å) auroral form observed in the daylit atmosphere below Hudson Bay by the Auroral Ionospheric Mapper instrument on the HILAT satellite. The magnetic field observed by HILAT in approximately the east-west geomagnetic direction is shown in the line plot on the right. In this plot, the vertical axis is the distance along HILAT's trajectory (which occurs down the middle of the image map), and the horizontal axis is the magnetic disturbance. The large magnetic disturbance near the top of the plot (first to the right and then to the left) reveals the presence of a pair of field-aligned currents. The current at the poleward side flows downward, while the current at the equatorward side flows upward and is located at the same position of the arc. The downward flowing electrons that carry the current also produce the arc. (The Auroral Ionospheric Mapper image was provided through the courtesy of R. E. Hoffman, AFGL, and C. I. Meng, APL.)

cipated. Many of the formal presentations have been published.[25] The knowledge in this field was reviewed and remaining questions were identified. Some questions concerning these currents include the following:

1. What is the precise role that Birkeland currents play in ionospheric plasma instabilities? The mere presence of these currents may not be sufficient to initiate the instabilities, but are the Birkeland currents the primary energy source for the growth of the instabilities? Is the fundamental boundary between the upward and downward flowing Region 1 and Region 2 currents an important source of instabilities? What role do Birkeland currents play as they flow to greater distances from the earth where the magnitude of the geomagnetic field is much smaller in comparison to the disturbance field of the currents?
2. What are the basic sources of large-scale Birkeland currents? It has become apparent that the solar wind and interplanetary magnetic field have an effect on the Birkeland currents, but is their ultimate source contained completely inside the magnetosphere? The sources of the complicated Birkeland currents in the dayside cusp and the nightside Harang region remain separate topics of research by themselves.
3. How are Birkeland currents connected to currents in the ionosphere? How are these circuits modified during active periods (substorms), different seasons, or different interplanetary conditions? Can the various surface and satellite magnetic field observations be explained with a unique current circuit?

Simultaneous observations of associated phenomena from single and multiple spacecraft such as HILAT, TRIAD, and the proposed NASA OPEN (Origins of Plasmas in the Earth's Neighborhood) program should provide some of the answers to these questions concerning Birkeland currents.

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