THOMAS A. POTEMRA

# STUDIES OF AURORAL FIELD-ALIGNED CURRENTS WITH MAGSAT

Electric currents that flow between the outermost boundaries of the magnetosphere and the auroral zones, sometimes deliver more power to the earth than is generated in the entire United States at any given time. These field-aligned "Birkeland" currents are detected on a regular basis by Magsat.

## INTRODUCTION

Following earlier suggestions by Edmund Halley and Anders Celsius that the auroral phenomena behave magnetically, Kristian Birkeland discovered in his polar expeditions of 1902-03 that large-scale currents were associated with the aurora. He was also the first to suggest that these currents originated far from the earth and that they flowed into and away from the polar atmosphere along the geomagnetic field lines. The existence of such field-aligned currents was widely disputed because it was not possible from a study of only surface magnetic field measurements to distinguish unambiguously between current systems that are field aligned[1] and those that are completely ionospheric.[2] Furthermore, theoretical calculations[3,4] predicted that the effects of field-aligned currents may be impossible to detect with ground-based magnetometers for certain models of these current systems.

The first experimental confirmation of the presence of field-aligned ("Birkeland") currents was provided by A. J. Zmuda and his colleagues[5,6] who studied magnetic disturbances in the polar regions of the earth, observed with the single-axis magnetometer used in the attitude determination system on the APL/U.S. Navy 5E-1 (1963-38C) satellite. That satellite, launched on September 28, 1963, into a nearly circular polar orbit at an altitude of 1100 km, carried an array of particle detectors and a fluxgate magnetometer.[7]

Zmuda[5,6] discovered that disturbances normal to the main geomagnetic field were often observed with 5E-1 in the same region of the earth associated with a variety of auroral phenomena. It was soon realized that the transverse disturbances could be interpreted as being caused by electric currents flowing along the geomagnetic field lines, and thus the first study of the global characteristics of Birkeland currents was begun at APL.

Recognizing the importance of sensitive satellite magnetic field measurements to the study of Birkeland currents, Armstrong and Zmuda[8] suggested a modification to the attitude magnetometer system for the APL/U.S. Navy Triad satellite. The Triad satellite was launched into a polar orbit at an altitude of 800 km on September 2, 1972, and, until the launch of Magsat on October 30, 1979, was the only satellite making continuous and high-resolution magnetic observations in the polar regions. The Triad magnetometer provides 2.25 vector samples per second with a resolution of 12 nanoteslas (1 nT = $10^{-9}$ weber per square meter), made possible by the 13-bit analog-to-digital converter incorporated into the system following the suggestion of Armstrong and Zmuda. The Triad magnetic field observations were used to determine for the first time the flow directions, spatial distribution, and intensities of Birkeland currents and their relationships to a variety of geophysical phenomena such as optical emissions, current-driven plasma instabilities, ionospheric currents, geomagnetic storms, and interplanetary phenomena. During its brief lifetime, the improved Magsat magnetic field observations were correlated with the Triad observations to compile more information about the important Birkeland currents and to calibrate the Triad magnetometer. Fortunately for these studies, Magsat was launched near the time of the peak solar cycle (the largest in many 11-year cycles) so that disturbances produced by the Birkeland currents were observed on almost every orbit.

The importance of Birkeland currents to the coupling between outer space and the auroral atmosphere is emphasized by their total intensity, which ranges between $10^6$ and $10^7$ A, and by the energy they dissipate in the upper atmosphere, which can exceed by a considerable factor the energy deposition associated with the dramatic, visual, auroral forms. The Birkeland currents are also the critical ingredient in a variety of complicated plasma phenomena that have important applications to earth (associated with substorms and the aurora), to Jupiter (associated with Io-related radio emissions),[9,10] and to the galaxy (related to comets and double radio sources).[11]

## MAGNETIC DISTURBANCES AND FIELD-ALIGNED CURRENTS

The magnitude and direction of equivalent currents associated with magnetic disturbances, $\Delta\vec{\mathbf{B}}$, are determined from the relationship $\vec{\mathbf{J}} = (1/\mu_0)$ curl $\Delta\vec{\mathbf{B}}$. The disturbances occur predominantly in the east-west (geomagnetic) direction so that $J = (1/\mu_0)(\partial/\partial x)\ \Delta By$, where $J$ is the density of the field-aligned current, $x$ is positive in the northward direction, and $\Delta By$ is the observed disturbance in the east-west direction.[12,13] In this case, the formula is the same as that for the transverse magnetic disturbance due to current sheets of infinite longitudinal extent. At the altitude of Triad, a change in $By$ equal to 100 nT over 1° of latitude is equivalent to a field-aligned current density of 0.64 $\mu A/m^2$. The magnitude of the current intensity, $\int Jdx$, is given directly by the amplitude of the magnetic disturbance $\Delta By$ by $\int Jdx = (1/\mu_0)\ \Delta By$. A 100 nT disturbance corresponds to a current intensity of 0.08 A/m.

An example of a transverse magnetic disturbance often observed with Triad is shown in Fig. 1 (from Ref. 13) with the deduced field-aligned current density and intensity.

## PRINCIPAL CHARACTERISTICS OF BIRKELAND CURRENTS

Large-scale Birkeland currents are concentrated in two principal areas that encircle the geomagnetic pole.[12-16] Figure 2 is a summary of the average spatial distribution in the northern high-latitude region determined from 493 Triad passes during weakly disturbed geomagnetic conditions and 366 Triad passes during an active period (from Ref. 16.) The Birkeland current flow regions have been arbitrarily designated by Iijima and Potemra [14,15] as

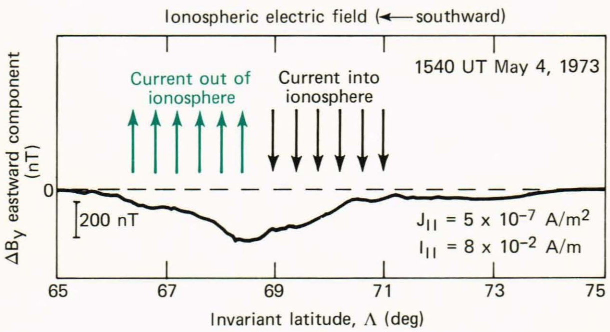


**Fig. 1—An example of a magnetic disturbance transverse** to the geomagnetic field measured by Triad on May 4, 1973 (from Zmuda and Armstrong[13]). The density and flow direction of the field-aligned currents producing these disturbances are determined from Maxwell's equation $\vec{J} = (1/\mu_0)$ curl $\Delta\vec{B}$ in the manner described in the text. The direction of the appropriate electric field, also shown, can produce a southward current flowing horizontally in the ionosphere to couple the upward and downward flowing field-aligned currents.

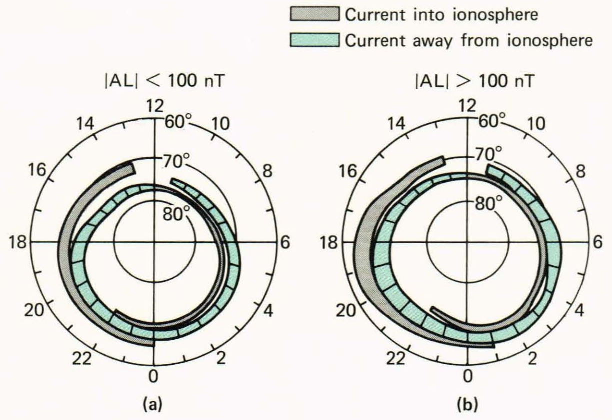


**Fig. 2—Statistical distributions of the location and flow** directions of large-scale Birkeland currents during weakly disturbed geomagnetic conditions (a) and during disturbed periods (b) (from Ref. 16).

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, whereas the Region 2 currents flow in the opposite direction at any given local time. The basic flow pattern of Birkeland currents remains unchanged during geomagnetically inactive and active periods (Fig. 2), although the regions widen and shift to lower latitudes during disturbed periods (similar to optical auroral forms by Feldstein[17]).

Figure 3 (from Ref. 18) is a schematic diagram of the large-scale Birkeland currents that flow into and away from the auroral regions shown in Fig. 2 and form cone-shaped regions. The current flow reverses direction near midnight and near noon. This current system is permanent, with the total amplitude ranging between $10^6$ and $10^7$ A, depending on the solar-terrestrial conditions. The striking visual forms of the aurora occur only when the incoming particles are energetic enough to penetrate to low altitudes and excite the atmospheric gas.

Analyses of Triad magnetometer data acquired over the south polar regions and recorded at McMurdo, Antarctica, indicate that the basic flow pattern shown in Fig. 2 for the north pole is the same for the south pole.[19] At any given local time and invariant latitude location, the field-aligned current flow is the same.

The average values of field-aligned current density and intensity in the various regions and sectors discussed above are listed in Table 1 (from Ref. 16). The total current, estimated by integrating the observed current intensity over the local time extent of the appropriate region, is also listed in Table 1. The total amount of current flowing into the ionosphere (including Regions 1 and 2) is always equal to the total current flowing away (within 5%) for every level of magnetic activity. The fact that current continuity is always preserved is important to

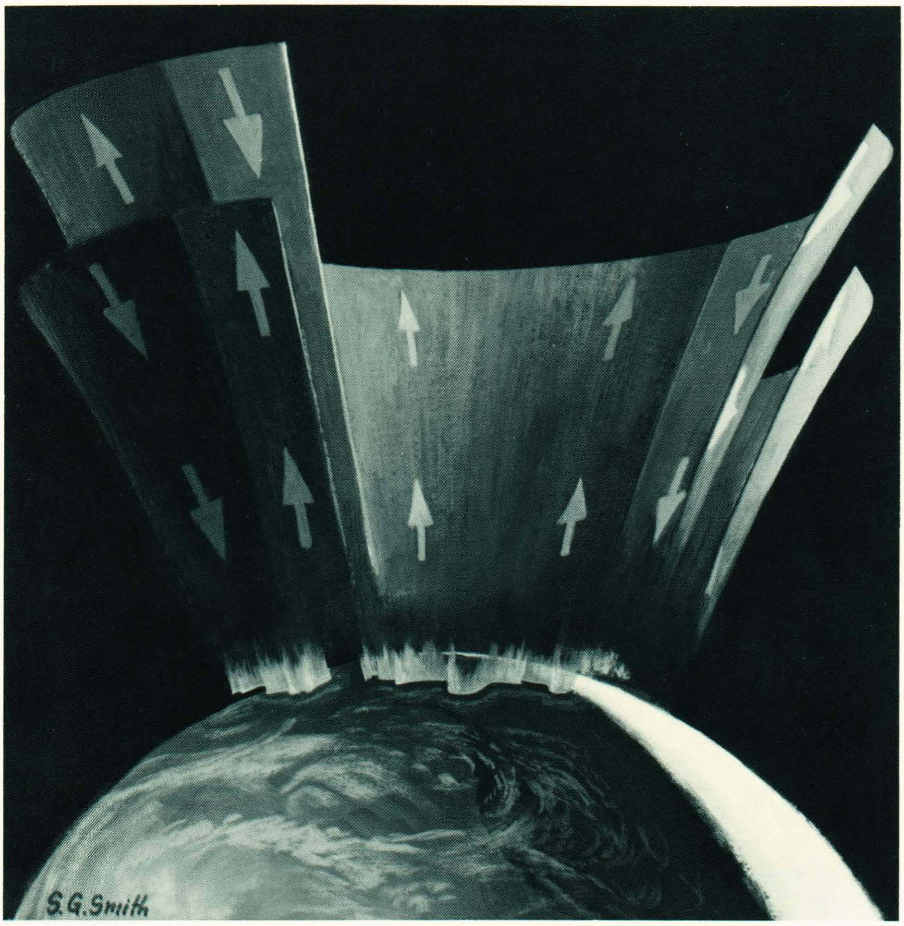


**Fig. 3—Cone-shaped regions** formed by Birkeland currents flowing into and away from the auroral region. The currents on a given sheet reverse direction near midnight and noon (from Ref. 18).

Table 1
AVERAGE CHARACTERISTICS OF LARGE-SCALE FIELD-ALIGNED CURRENTS

| | *Afternoon to Midnight* | | *Midnight to Forenoon* | |
|---|---|---|---|---|
| *Parameter* | *Region 1* | *Region 2* | *Region 1* | *Region 2* |
| Current density ($\mu A/m^2$) | | | | |
| Quiet | −0.9 | 0.3 | 0.9 | −0.5 |
| Disturbed | −1.4 | 0.7 | 1.5 | −1.1 |
| Total current ($10^6$ A) | | | | |
| Quiet | −1.3 | 0.8 | 1.5 | −1.1 |
| Disturbed | −2.8 | 2.6 | 3.2 | −3.3 |

A positive value denotes current flow into the ionosphere.
A negative value denotes flow away from the ionosphere.
Values are averages over specified regions.

the development of the models of the three-dimensional current system that couples the magnetosphere with the lower atmosphere and ionosphere. It is also significant that the total field-aligned current in Region 1 is significantly larger than the Region 2 total current during relatively quiet conditions, while during active periods the total current flow in both regions becomes nearly equal.

## MAGSAT OBSERVATIONS OF BIRKELAND CURRENTS

The Magsat spacecraft was launched into a dawn-dusk synchronous orbit, whereas Triad is in a polar orbit and appears to precess westward with respect to the earth-sun line at a rate of approximately a degree per day. The orbital planes of the two spacecraft were nearly coincident in November 1979, when magnetic field measurements were made at nearly the same point in time and space (separated only by their altitude difference and the time differential related to their orbital periods — a value that cannot exceed one-half the orbit period, or approximately 50 minutes, when they are moving in the same direction). Data were acquired by Magsat and Triad during a disturbed period on November 7, 1979 at nearly the same place in the north auroral region. Segments of their orbital tracks are shown in Fig. 4 superimposed on the statistical distribution of Birkeland currents shown in Fig. 2 determined for disturbed conditions. The Triad observations were made at 17:12:30 UT, and the Magsat observations 25.5 minutes later (at 17:38 UT). Regions of upward- and downward-flowing Birkeland currents detected by Magsat and Triad are shown by the shaded areas of Fig. 4. They are coincident and are close to the statistical distribution. The orientations of the transverse magnetometer axes (denoted A and B) for the two spacecraft with respect to their velocity vectors are shown in the upper right corner of Fig. 4. The A and B axes for Triad are directed 135 and 45°, respectively, from the velocity vector, and for Magsat are parallel and normal, respectively, to the velocity vector.

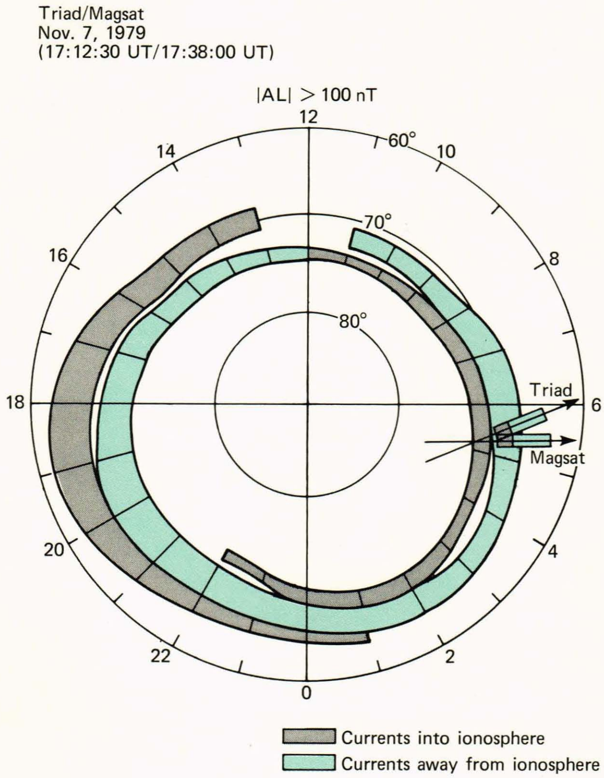


**Fig. 4—Orbital tracks of Triad and Magsat superimposed** on the statistical pattern of Birkeland currents shown in Fig. 2. The locations and flow directions of the Birkeland currents detected by the two satellites are shown by the shaded areas.

Theoretical magnetic field values (computed from the 1965 Model International Geomagnetic Reference Field) extrapolated to the period of observation were subtracted from the Triad and Magsat observations. The resulting disturbance vectors were rotated from the spacecraft coordinate systems to the geomagnetic reference frame. The components in the geomagnetic east-west direction (i.e., tangent to the circles in Figs. 2 and 4) from Triad and Magsat are shown in Fig. 5. These preliminary data show the amazing similarity of the details in the transverse magnetic disturbances measured by different spacecraft. The disturbances are over 1000 nT and can be interpreted as resulting from a pair of intense Birkeland currents flowing into the ionosphere between about 67 and 65° magnetic latitude and away from the ionosphere between about 65 and 61° magnetic latitude. The density of these currents is about 2 $\mu A/m^2$ and their intensity is about 0.8 A/m.

The processing of the Magsat data is in a preliminary stage and work is only beginning on the investigation of disturbances associated with Birkeland currents. The spatially separated measurements provided by Magsat and Triad will permit the determination of the spatial extent of the Birkeland currents and of the differences, if any, in the intensities of these currents over sunlit and dark portions of the polar ionosphere. The improved sensitivity of the Magsat magnetometer and its lower altitude (in comparison to Triad) will also provide data on the potential field contribution of ionospheric auroral currents that flow at an altitude of about 100 km (the magnetic effects of which have been observed on the ground on a regular basis since Birkeland's original work). The ultimate objective of these studies is to understand and define the variable high-latitude magnetic disturbances to assist in the Magsat program's goal of obtaining an accurate, up-to-date quantitative description of the earth's main geomagnetic field.

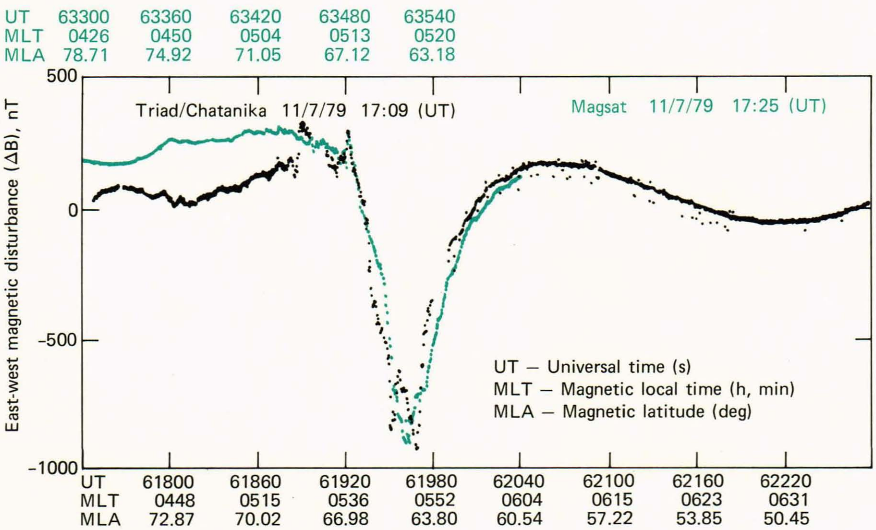


**Fig. 5—The geomagnetic east-west** component determined from the Magsat and Triad observations. The horizontal scale lists universal time (UT) in seconds, magnetic local time (MLT) in hours and minutes, and magnetic latitude (MLA) in degrees.

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