AURORAL FIELD-ALIGNED CURRENTS: APL'S CONTRIBUTION TO THEIR DISCOVERY

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Early History

The association of disturbances of the earth's magnetic field with auroral displays dates back to Halley and Celsius in the 18th century.[1] In the 19th century, Gauss suggested the possibility of electric currents from the sun to explain magnetic disturbances, and at the end of the same century, Kristian Birkeland refined that idea to suggest that these solar currents were connected to currents in the auroral zones. Birkeland recognized that the geomagnetic disturbances recorded on the earth's surface below the auroral region were due to intense currents flowing horizontally in the ionosphere above. They are referred to today as auroral electrojets, currents resulting from large-scale electric fields directed perpendicularly to the geomagnetic field. Birkeland suggested[2] that the horizontal currents were connected to outer space by a system of currents flowing up and down along the geomagnetic field lines as shown in Fig. 1.

The existence of field-aligned currents (later referred to as Birkeland currents) was disputed because it is not possible to identify them unambiguously from surface magnetic field measurements. Sydney Chapman, for example, wrote several papers (see Ref. 3, for example) that included elegant mathematical descriptions of current systems contained completely within the earth's ionosphere. These currents could adequately account for surface magnetic variations (see Fig. 2, for example). It has been suggested that Chapman was inspired by Lord Kelvin, president of the Royal Society, who proclaimed in 1893 that "the supposed connection between magnetic storms and sunspots is unreal."[4] Hannes Alfvén championed the idea of field-aligned currents and their importance to auroral physics, but because he was 20 years younger than Chapman, he had an uphill battle. A paper published in 1938 by E. H. Vestine and Chapman states that "the electric current system of Birkeland gives rise to a disturbance-field shown to be inconsistent with observations in several important respects."[5] A year later, Alfvén published an article that incorporated the Birkeland field-aligned current system as shown in Fig. 3.[6]

The controversy concerning the existence of field-aligned currents continued through 1967, when a symposium on aurora and magnetic storms was held in Sandefjord, Norway, to honor the 100th anniversary of Birkeland's birth. Chapman, as the most eminent geomagnetic scientist of the time, was invited to give the opening scientific address. The audience was somewhat surprised to hear him say, "The apparently unshakable hold, on Birkeland's mind, of his basic but invalid conception of intense electron beams, mingled error inextricably with truth in the presentation of his ideas and experiments on auroras and magnetic storms."[7]

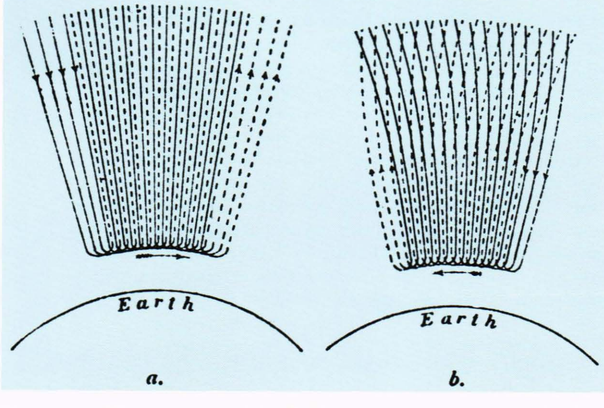

Figure 1—The system of field-aligned currents suggested by Birkeland in 1908 (Fig. 50 from Ref. 2).

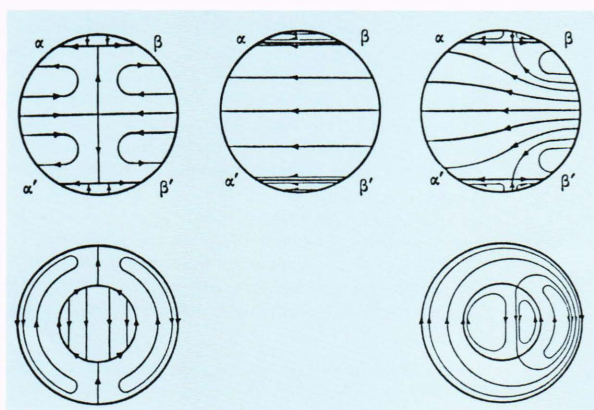

Figure 2—Five figures showing the atmospheric current systems developed by Chapman in 1927 (Figs. 7, 8, and 9 from Ref. 3). The upper three figures represent the view of the terrestrial current systems as seen from the sun, and the lower two figures are the views over the north pole (with "noon" at the bottom and "midnight" at the top of each).

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The Amplitude Distribution of Field-Aligned Currents at Northern High Latitudes Observed by Triad

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The spatial distribution and magnitudes of field-aligned currents at 800-km altitude over northern high latitudes were determined from Triad magnetometer data recorded at College, Alaska, during the period from July 1973 to October 1974. The characteristics that were determined include the following: (1) Large-scale field-aligned currents are concentrated in two principal areas encircling the geomagnetic pole: region 1, located near the poleward part of the field-aligned current region; and region 2, located near the equatorward part. (2) In region 1 during moderately disturbed conditions ($2- \leq Kp \leq 4+$) the largest current densities occur in the forenoon sector, with currents flowing into the ionosphere (with a peak value of $\sim 2\ \mu A/m^2$ between 0700 and 0800 MLT), and in the afternoon sector, with currents flowing away from the ionosphere (with a peak value of $\sim 1.8\ \mu A/m^2$ between 1500 and 1600 MLT). These areas of maximum current density in region 1 are approximately coincident with the location of the foci of the Sq^p current system. (3) In region 2 for $2- \leq Kp \leq 4+$ the largest current densities occur on the night side where auroral electrojets are usually most active, namely, in the evening to premidnight sector, with currents flowing into the ionosphere (with a peak value of $\sim 1\ \mu A/m^2$ between 2100 and 2300 MLT), and in the midnight to morning sector, with currents flowing away from the ionosphere (with a peak value of $\sim 1.3\ \mu A/m^2$ between 0200 and 0300 MLT). (4) The currents in region 1 are statistically larger than the currents in region 2 at all local times except for the sector near midnight (~2100–0300 MLT), where the region 2 currents are comparable to or slightly larger than the region 1 currents. (5) The region 2 currents in the midnight to morning sector are correlated with the intensity of the westward electrojet, and the region 2 currents in the evening to premidnight sector are correlated with the intensity of the eastward electrojet. (6) The region 1 currents appear to persist, especially on the day side, even during very low geomagnetic activity with a value of current density $\gtrsim 0.6\ \mu A/m^2$ for $Kp = 0$. We suggest that the magnetosphere-ionosphere current system which contains field-aligned currents consists of two distinct parts: a permanent part with field-aligned currents in region 1 and the other part having field-aligned currents in region 2, which is an important element of the auroral electrojets.

INTRODUCTION

The concept of field-aligned currents in the polar regions was introduced by *Birkeland* [1908], but not until 1966 did satellite observations of magnetic disturbances transverse to the main geomagnetic field provide the most direct evidence for their existence [*Zmuda et al.*, 1966, 1967]. Field-aligned currents are important because of the role that they are expected to play in the coupling between the magnetosphere and the ionosphere and their relationship to auroral phenomena and substorms [*Boström*, 1964, 1974; *Fukushima*, 1969; *Vasyliunas*, 1970; *Anderson and Vondrak*, 1975].

During the last few years several observations of field-aligned currents have been reported by virtue of their associated magnetic variations. Among these have been the observations of magnetic disturbances in the auroral region and polar cap using the Azur satellite with a two-axis magnetometer system by *Theile and Praetorius* [1973] at altitudes between 400 and 3100 km, the three-axis measurements by the Imp 4 and Imp 5 satellites in the magnetotail plasma sheet by *Fairfield* [1973], and the three-axis measurements on the Ogo 5 satellite by *Sugiura* [1975] at altitudes of $>4\ R_E$. Transverse magnetic disturbances ascribable to field-aligned currents have also been observed at the synchronous altitude with the ATS 1 satellite on the night side by *Coleman and McPherron* [1970] and *Iijima* [1974]. The many rocket observations of field-aligned electron precipitation reviewed by *Arnoldy* [1974] have, for specific auroral events, identified the particles responsible for the field-aligned currents and their relationship to visual auroral arcs. However, the Triad satellite has to date obtained the only continuous three-axis, high-resolution magnetic measurements at relatively low altitudes (~800 km) in the high-latitude regions.

The vector magnetometer experiment on board Triad is described in detail by *Armstrong and Zmuda* [1973] and has been used to map the spatial location of transverse magnetic disturbances in the northern polar region for $Kp \leq 2+$ and $Kp \geq 3-$ [*Zmuda and Armstrong*, 1974*a*]. *Zmuda and Armstrong* [1974*b*] and *Armstrong* [1974] have used Triad data to determine for the first time the flow directions of field-aligned currents at all magnetic local times in the northern auroral region. These studies showed that the region of the transverse magnetic disturbances was statistically coincident with the visual auroral oval defined by *Feldstein* [1966] and that the associated field-aligned currents had the following characteristic directions: (1) into the ionosphere at the polar boundary and away from the ionosphere at the equatorward boundary of the field-aligned current region during the morning hours and (2) away from the ionosphere at the polar boundary and into the ionosphere at the equatorward boundary during the afternoon and evening local times. Recently, *Sugiura and Potemra* [1976] have studied net field-aligned currents in the high-latitude region using the Triad data.

As an extension of the study of field-aligned currents with the Triad satellite we present results of the detailed analysis of more than 1300 passes of Triad recorded at College, Alaska, over the northern high-latitude region during the 16-month period from July 1973 to October 1974. The spatial distribution and the magnitudes of field-aligned currents and their dependence upon geomagnetic activity as measured by

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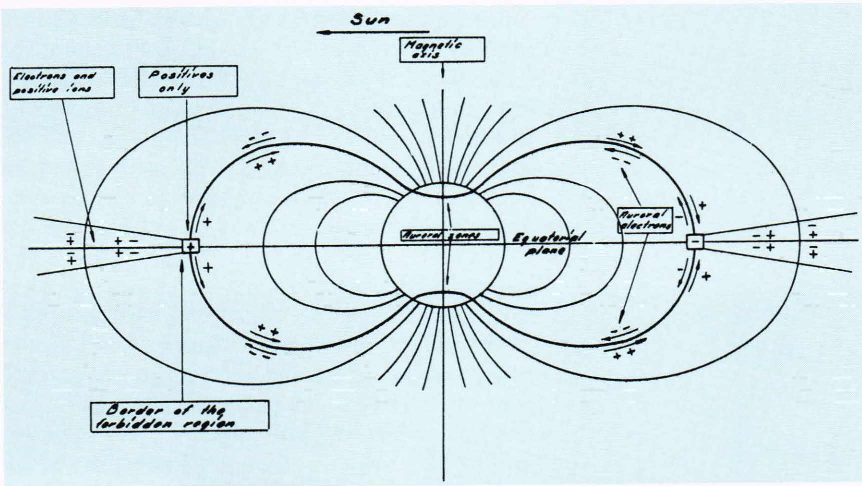


Fig. 5. The discharge along the magnetic lines of force between the equatorial plane and the auroral zones.

Figure 3—The system of auroral currents proposed by Alfvén in 1939 (Fig. 5 from Ref. 5).

Alfvén would often remark, "Now that satellites are orbiting the Earth, we shall see which current system is correct, the one described by Birkeland or the one described by Chapman and his students (principally Vestine)."[4] The evidence for the existence of field-aligned currents was provided by Alfred Zmuda, John Martin, and Ted Heuring of APL with magnetic field observations from the APL-built Navy navigation satellite 1963-38C.

Zmuda's Geomagnetic Research

Alfred J. Zmuda joined APL in 1951 immediately following the receipt of his Ph.D. degree in physics from The Catholic University of America the same year. He wrote his thesis, *Dispersion of Velocity and Anomalous Absorption of Ultrasonics in Nitrogen*,[8] on an experiment he performed. Zmuda never directly conducted experiments again and devoted his subsequent work to the study of the earth's magnetic field and its mathematical description. The first paper he published as an APL scientist, "Vertical Extrapolation of Geomagnetic Field Components," authored by him and Lowell McClung of APL, appeared in *Transactions of the American Geophysical Union* in December 1955.[9]

Al's work in geomagnetism was inspired by E. H. (Harry) Vestine, who received his Ph.D. degree under Chapman in 1937. Vestine was a member of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, from 1938 to 1957. In the period following World War II, Vestine conducted magnetic field observations from captured German V-2 rockets. These were done with James A. Van Allen, then of APL, who conducted radiation experiments, and John J. Hopfield of The Johns Hopkins University, who performed solar Lyman-α experiments.[10]

Vestine was the Secretary General of the World Magnetic Survey Board when he died in 1968, and Zmuda immediately succeeded him in that position. As the leader of the World Magnetic Survey, he directed the consolidation of magnetic field observations conducted by many countries using surface observations, ships, aircraft, and satellites that resulted in the development of the first International Geomagnetic Reference Field (referred to as the IGRF 1965.0). That model field is described with values for the coefficients of the "best-fit" spherical harmonic expansion representation of the measured field. The IGRFs are updated periodically and have most recently incorporated the data acquired by the APL-built MAGSAT satellite.

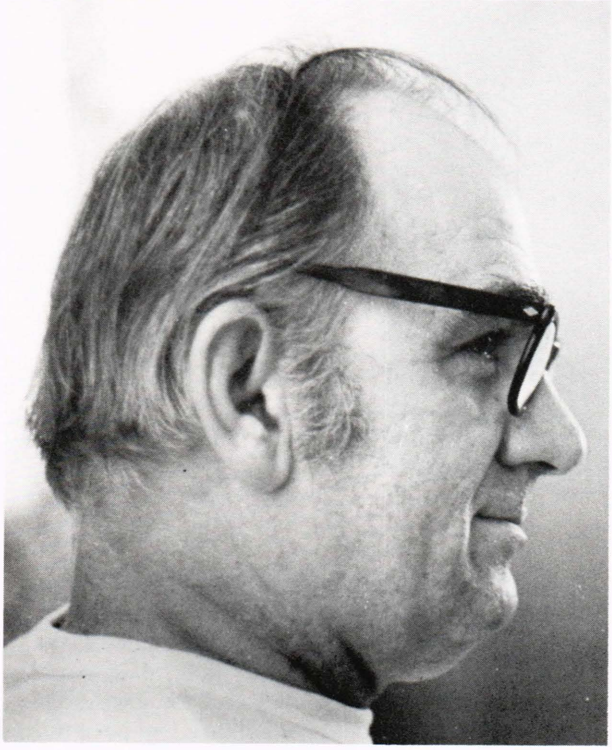
I joined APL in 1965 to work with Zmuda, and we shared an office from then until his death in 1974, when I continued his work on field-aligned currents. Considering the history, one can imagine a "spiritual" link back to Chapman through Vestine and Zmuda.

Satellite 1963-38C

By the 1960s, Zmuda was internationally respected as an authority on the geomagnetic field and was APL's resident expert on the subject. It was therefore no surprise that he was called on when the APL-built Navy navigation satellite 1963-38C detected unusual magnetic disturbances at high latitudes. The satellite was launched on September 28, 1963, into a nearly circular polar orbit at approximately an 1100-kilometer altitude. As part of the attitude determination system, 1963-38C (which never had a more becoming name, but was also referred to as 5E-1) carried a vector fluxgate magnetometer.

The satellite was tracked and commanded from the APL-based ground station. It was the first APL/Navy navigation satellite that could "lock the commutator" on command so that the data from any given experiment could be recorded continuously. Readings from the magnetometer were normally read out no faster than every minute or so, but, as a demonstration, the ground station locked on a single axis of the magnetometer so that the earth's magnetic field could be monitored on a continuous and real-time basis. In this mode of operation, unexpected magnetic disturbances were detected when the satellite was at high latitudes.

I would occasionally accompany Zmuda on a walk to the ground station when alerted to the fact that a high-



Alfred J. Zmuda, 1921-1974.

latitude pass of 1963-38C was imminent. We could see firsthand the perturbations to the magnetic field as the satellite flew through what we now know is the auroral zone.

Zmuda dutifully filed the visicorder charts (which had a tendency to fade because they were made on photosensitive paper) of magnetic field data in brown APL envelopes. He and Heuring would patiently spread out each recorder sheet (which was several feet long) in our office and would determine with expandable Gerber scales when the magnetic disturbances occurred and how large they were. Zmuda determined that they occurred principally transverse to the main geomagnetic field in the east–west direction and in the high-latitude region associated with the auroral zone. He included the findings in "Transverse Magnetic Disturbances at 1100 Kilometers in the Auroral Regions," a paper by himself, John Martin (the electrical engineer responsible for the satellite's magnetometer), and Ted Heuring that was personally reviewed by Alex Dessler, editor of the *Journal of Geophysical Research.* Alex recognized the profound nature of the 1963-38C observations because they provided the first experimental evidence for the existence of field-aligned currents and hence would prove Chapman wrong and Alfvén right. In that early paper, published in November 1966, Zmuda did not specifically attribute the observations to field-aligned currents. Dessler, in the "anonymous referee" response, suggested that the paper be expanded to include a mention of field-aligned currents. I can remember Zmuda reading the referee's response in our office and saying something like, "This is a wonderful suggestion, field-aligned currents must be the explanation!" Zmuda refused to include a strong reference to field-aligned currents because he felt that the idea was not his and that the "unknown" referee deserved the credit for the idea. Consequently, the Zmuda et al. paper[11] was published as is, and Dessler published a paper in February 1967 with his student, W. D. Cummings,[12] with the suggestion that the transverse magnetic perturbations could be explained by field-aligned currents.

The satellite also carried an array of particle spectrometer experiments to determine the space environment. As a test Navy navigation satellite, it became one of the most productive ever launched. Data were acquired routinely for more than six years, and the satellite was working 11 years later when, on September 27, 1974, an APL symposium was held describing the scientific results. Over 40 papers were published on data acquired by the satellite, including those on the field-aligned current studies and on the Van Allen radiation belt, solar protons, and energetic particle effects on the lower ionosphere. The first study of the decay of radiation from the Starfish Artificial Electron Belt was made with the 1963-38C data.[13]

The TRIAD Satellite

Zmuda recognized the importance of the field-aligned currents to an understanding of auroral and space physics and requested that the TRIAD satellite,[14] scheduled to be designed and built at APL, be equipped with an improved magnetometer system. (The name TRIAD is derived from Transit Improved And DISCOS; DISCOS is the acronym for a Disturbance Compensation System.[14]) TRIAD required a magnetometer system for attitude determination, but with far less resolution than the 12 nanoteslas proposed by Zmuda. A resolution of 700 nanoteslas is required to determine a satellite's attitude within 1 degree in a 40,000-nanotesla total field. TRIAD was to be the first APL/Navy navigation satellite with a programmable computer. Zmuda appealed to the Space Department Head, Richard Kershner, to include a special 13-bit analog-to-digital converter to provide the 12-nanotesla resolution. Kershner agreed, but only with the proviso that the system have no effect on the satellite's major mission and that it be separate and independent from TRIAD's central computer. TRIAD was launched on September 2, 1972, on a Scout rocket from Vandenberg Air Force Base in California and was a complete success. Later on, anomalies in the onboard central computer limited the amount of data from the spacecraft that could be transmitted to the ground. However, the separate data system for the magnetometer worked perfectly, and the telemetry system was then available to transmit the magnetic field measurements on a continuous basis, which it did for over 11 years!

The continuous high-resolution magnetic field observations acquired by TRIAD allowed Zmuda and James Armstrong, a young APL physicist, to determine the first statistical map of field-aligned currents and their flow directions in the auroral zone. The map (Fig. 4) was published as Fig. 9 in "The Diurnal Flow Pattern of Field-Aligned Currents" by Zmuda and Armstrong, which ap-

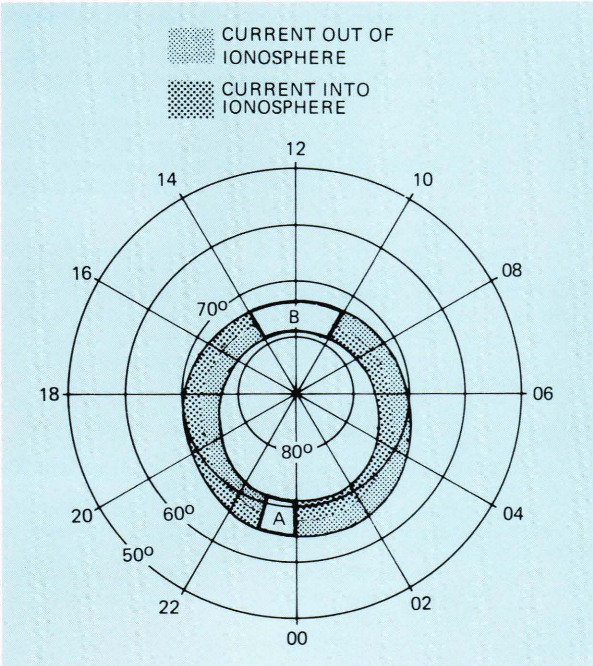


Figure 4—The spatial distribution of field-aligned currents and their flow direction determined from the analysis of TRIAD data by Zmuda and Armstrong (1974). This is a magnetic latitude and magnetic local time plot and is the first attempt to map the location of field-aligned currents in the auroral zone using satellite data.

peared in the *Journal of Geophysical Research* on November 1, 1974. Both Zmuda and Armstrong died during the summer of 1974 before they were able to see their article in print. The impact that this first map of field-aligned currents had on the scientific community is demonstrated by the large number of times it was cited. Their work on field-aligned currents began a close and long friendship between APL and Alfvén.

I continued the field-aligned current studies using the TRIAD data with the help of Masahisa Sugiura, a close personal friend of Zmuda, from NASA's Goddard Space Flight Center, and Takesi Iijima, from the University of Tokyo, who had planned to spend 1975 at APL as a visiting scientist working with Zmuda. We benefited from extraordinary cooperation from the Space Department, from APL, and from the international community of scientists in continuing the TRIAD studies. Scientists at the University of Alaska assisted in recording TRIAD data from a portable station moved there. An automatic station was designed and built from surplus receivers and parts to recognize and record TRIAD data. The National Science Foundation and the Office of Naval Research continued the support of the APL research program begun by Zmuda and Armstrong. Automatic ground stations were set up in Fairbanks, Alaska; McMurdo, Antarctica; Resolute, Canada (near the magnetic pole); Kiruna, Sweden; Thule, Greenland; and Lauder, New Zealand, with the help of local scientists and often at no cost.

Iijima, Sugiura, and I continued the study of the characteristics of field-aligned currents, and the first three

Nobel Laureate Hannes Alfvén (Royal Institute of Technology, Stockholm, and University of California, San Diego) with Potemra admiring the map of field-aligned currents shown in Fig. 5 (photograph taken in 1976).

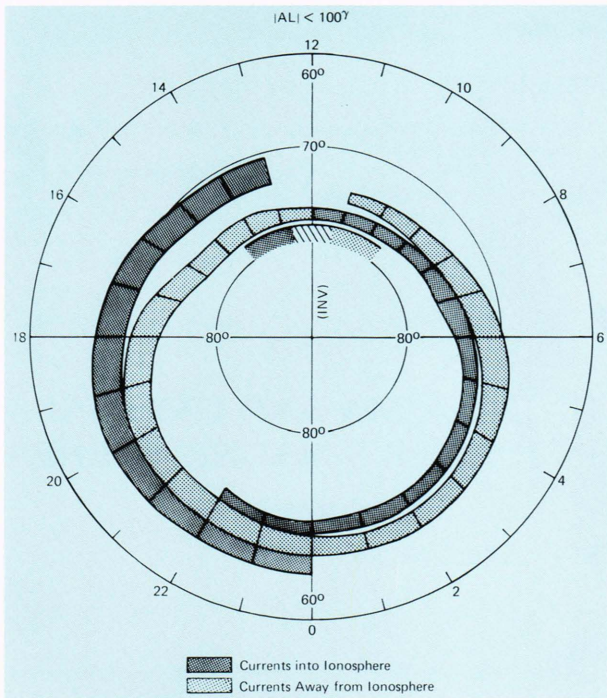


Figure 5—The refinement of the Zmuda/Armstrong field-aligned current map by Iijima and Potemra (1976), constructed from the analysis of nearly 500 TRIAD orbits.

papers that we published together are now on the most-cited list. Using the TRIAD data, we determined statistical patterns of field-aligned current locations, flow directions, intensities, and their relationship to geomagnetic conditions. The most referenced figure in these papers is shown here as Fig. 5 and is a refinement of the earlier map of Zmuda and Armstrong. Our statistical pattern of field-aligned currents was popular because it provided a reference frame for other studies of auroral phenomena such as particle precipitation, auroral emissions, ionospheric plasma convection patterns, and electric fields. By 1983, when TRIAD was 11 years old, over 50 scientific articles had been published on studies of the data, written by 37 different authors throughout the world, including the U.S., U.S.S.R., the People's Republic of China, Japan, and Europe. Many of these scientists participated in a special American Geophysical Union Chapman Conference on "Magnetospheric Currents" held in April 1983. TRIAD's birthday was celebrated at that conference and a selection of the papers was published.[15]

Field-aligned currents (now often referred to as Birkeland currents) are important because they provide a link between the lower auroral ionosphere and the magnetosphere and interplanetary medium. They are also the source of a variety of interesting plasma phenomena in the earth's neighborhood. The important role that field-aligned Birkeland currents have in the flow of energy between the sun and the earth (as suggested by Gauss and Birkeland, but refuted by Kelvin and Chapman) becomes more evident with the improvement of satellite experiments and the advent of multisatellite observational programs.

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HOT PLASMA AND UNUSUAL COMPOSITION IN JUPITER'S MAGNETOSPHERE

STAMATIOS M. KRIMIGIS

S. M. Krimigis, T. P. Armstrong, W. I. Axford, C. O. Bostrom, C. Y. Fan, G. Gloeckler, L. J. Lanzerotti, E. P. Keath, R. D. Zwickl, J. F. Carbary, and D. C. Hamilton, "Low Energy Charged Particle Environment at Jupiter: A First Look," *Science* **204**, 998-1003 (1979).

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The genesis of the two papers by Krimigis et al., published in 1979, that detailed the Voyager observations at Jupiter actually came eight years earlier when several of the co-authors joined a team to propose participation in the then recently announced opportunity for an "Outer Planets Grand Tour" program that envisioned sending two spacecraft to successively encounter Jupiter, Saturn, and Pluto and Jupiter, Uranus, and Neptune. Traditionally, the opportunities for such prestige missions in particle measurements had been preempted by the "Big Three" of space science at that time, namely, James Van Allen of the University of Iowa, John Simpson of the University of Chicago, and Frank McDonald, then at NASA's Goddard Space Flight Center. Our proposal represented an attempt by their former students and our contemporaries to introduce a new generation of state-of-the-art instrumentation into the study of magnetospheres.

Following evaluation of the proposals, our team was selected to participate in the definition phase of the Outer Planets mission with Robbie Vogt of Cal Tech (who proposed with McDonald) as the team leader and, in a gesture by NASA toward the younger generation, my-