Physica Scripta Vol. T60, 107–112, 1995

Alfvén Waves and Birkeland Currents

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Received 7 July 1995; accepted 12 July 1995

Abstract

Hannes Alfvén developed concepts over a half-century ago that continue to influence and guide modern space plasma physics. He derived the guiding center approximation for determining the motion of charged particles in a magnetic field and introduced the idea of a partial ring current formed from trapped radiation in the Earth's magnetic field. He expanded on the suggestion of electric currents flowing into and away from the auroral regions along geomagnetic field lines that was made at the turn of the century by the Norwegian scientist, Kristian Birkeland. Alfvén introduced the concept of a new type of wave motion that involved the coupling between mechanical and electromagnetic fields. These waves are called magnetohydrodynamic waves and are also commonly referred to as "Alfvén waves." In his theory of the origin of the solar system, Alfvén proposed that when a neutral gas streams through a plasma across magnetic field lines at sufficiently high velocity, a discharge-like process can occur in which the neutral gas begins to ionize rapidly. His "Critical Ionization Velocity" (CIV) effect has been demonstrated in laboratory experiments and in space. He applied Langmuir's theory of a probe in a plasma to explain the acceleration of electrons along geomagnetic field lines by "double layers" which produced aurora. Alfvén's ideas were not immediately accepted. His view of Birkeland currents became a source of controversy and intense debate for decades, which could be resolved only after the dawn of the space age. Alfvén regarded the space age as being a revolution in science, comparable to the introduction of the telescope by Galileo. He pointed out the ability of spacecraft to observe a wide range of physical parameters in comparison to the limited "visual light universe" based on ground based telescopes. An enormous amount of data is collected every day from a fleet of international satellite missions which depend upon the plasma physics principles introduced by Hannes Alfvén for interpretation and analysis. This paper describes a small fraction of the ever-increasing knowledge base derived from these space missions, concerning our understanding of Birkeland currents and Alfvén waves.

1. Historical introduction

According to Chapman and Bartels [1] the connection between aurora and magnetic storms was first suggested by Halley in 1716. Similar independent discoveries were made by Celsius, Hiorter and Wilcke the same century [2]. Inspired by his famous terrella experiments and by his extensive studies of geomagnetic data recorded during magnetic storms, Birkeland suggested at the end of the 19th century, that the aurora was due to cathode rays or similar 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 (referred to today as the auroral electrojets). In Birkeland's [3] 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 500,000 and a million Amperes and he determined that the altitude of these currents was located above 100 km. Birkeland's values are close to the intensities and altitudes determined from modern-day experiments. [4–7].

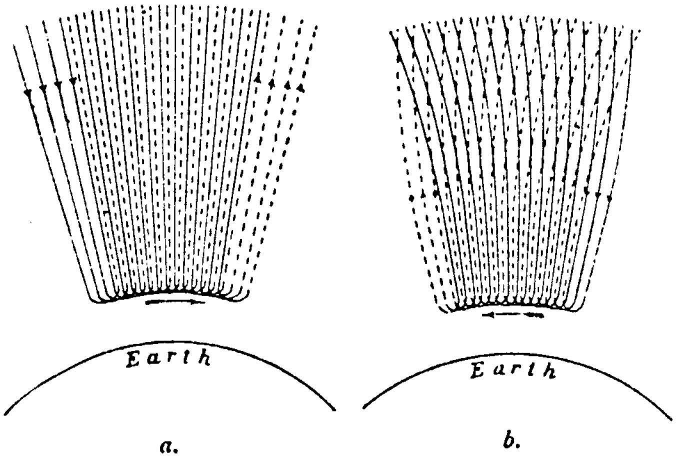

Fig. 1. The system of field-aligned currents originally suggested by Birkeland in 1908. "Figure 50a represents those in which the current-directions at the storm-centre are directed westwards, and 50b those in which the currents move eastwards" [3].

Birkeland was curious as to how the horizontal currents were connected ultimately to the Sun as 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 based upon his terrella experiments and on Störmer's calculations, and proposed the field-aligned current system reproduced here as Fig. 1. His two suggestions were to evolve into a controversy concerning the current system which was to continue 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 Chapman and his colleagues, and the model with the field-aligned currents was developed and advanced by Alfvén.

Störmer published a diagram of "descending corpuscles on the earth so as to produce an auroral arc," reproduced here as Fig. 2, which is very close to accounting for modern spacecraft observations of field-aligned Birkeland currents [8].

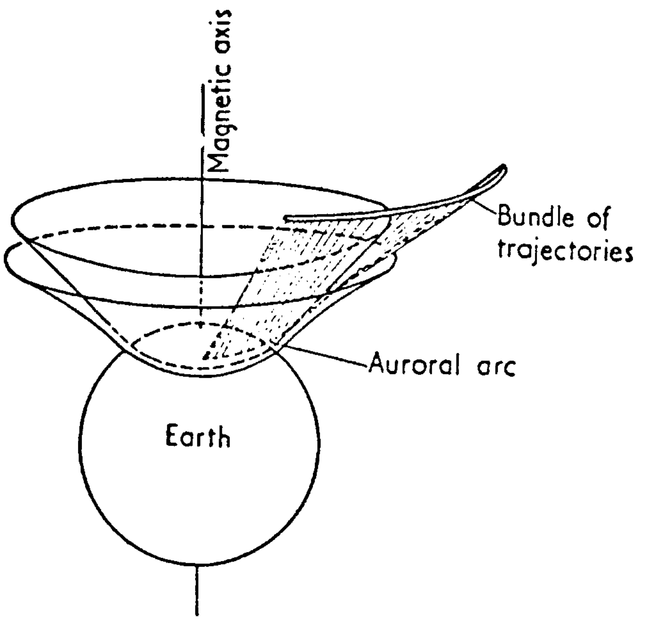

Fig. 2. Schematic diagram of "narrow region to which corpuscles descending on the Earth are confined so as to produce an auroral arc", developed by Störmer [2].

The reluctance to accept the concept of Birkeland's currents is illustrated by the following statements. "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." [9] The criticism became stronger, "The electric current-system of Birkeland gives rise to a disturbance-field shown to be inconsistent with observations in several important respects." [10]

Not only did he support the concept of field-aligned currents, Alfvén developed a theory for the generation of these currents. This is contained in the famous paper, "A Theory of Magnetic Storms and the Aurorae" by Alfvén published in the "Proceedings of the Royal Swedish Academy of Sciences," (Kungliga Svenska Vetenskapsakademiens Handlingar) [11]. Figure 3 from this paper shows Alfvén's diagram of these currents associated with the aurora. This remarkable paper contains concepts that continue to influence and direct modern-day space plasma physics. It was here that Alfvén developed the guiding center approximation for determining the motion of charged particles in a magnetic field and introduced the concept of a partial ring current formed from trapped radiation in the Earth's magnetic field. For a modern discussion of this paper, see "Magnetic Storms and the Aurorae: Comments and Annotations on a paper by Hannes Alfvén" by A. J. Dessler and J. M. Wilcox [12].

Another of his many seminal papers, "Existence of Electromagnetic-Hydrodynamic Waves" was published in *Nature* in 1942 [13]. In this paper, Alfvén examined the motion of "a conducting liquid in a constant magnetic field." He combined Maxwell's equations with the hydrodynamic equation and derived, for the first time, the equation for, in his words, "Electromagnetic-Hydrodynamic waves", known today as Magnetohydrodynamic, MHD, waves and also "Alfvén waves." Alfvén predicted in this paper that, "Waves of this sort may be of importance in solar physics." He was certainly correct, but underestimated the profound influence that his formulation for these plasma waves would have on the interpretation of a wide variety of phenomena in the Earth's and other planets' magnetospheres and in our solar system and in the universe.

Hannes Alfvén consolidated the 1939 and 1942 papers described above with several others into his book, "Cosmical Electrodynamics," published in 1950 [14]. This book, revised by Alfvén in 1981 [15] still serves as the "Bible" for many space physicists. The Table of Contents of this book lists almost all aspects of Space Physics and continues to be the agenda for present-day space physics research programs. The major chapter headings are listed below:

I. GENERAL SURVEY
II. ON THE MOTION OF CHARGED PARTICLES IN MAGNETIC FIELDS
III. ELECTRIC DISCHARGES IN GASES
IV. MAGNETO-HYDRODYNAMIC WAVES
V. SOLAR PHYSICS
VI. MAGNETIC STORMS AND AURORAE
VII. COSMIC RADIATION

This paper will describe satellite observations which have contributed to an understanding of auroral current systems (included in Alfvén Chapter VI) and of MHD waves (his Chapter IV).

2. Magnetospheric currents

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 as depicted in Fig. 4 by the continuous flow of the solar wind. This distortion requires the existence of a complicated set of currents, shown in this figure, flowing within the distorted magnetic field configuration called the magnetosphere. The compression of the geomagnetic field by the solar wind plasma on the dayside of the Earth gives 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, field-aligned Birkeland currents that flow along geomagnetic field lines into and away from the 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 later currents, known as the "auroral electrojets" were described accurately in Alfvén's 1950 book, "Cosmical Electrodynamics" [14]. On page 175 he states: "Investigations of the disturbance field near the auroral zones have shown that it may be attributed to currents in the upper atmosphere flowing along these zones at a height of a hundred or a few hundred kilometers above the earth's surface. The current is directed westwards on the morning side and eastwards on the evening side of the earth. Hence the currents being positive charge from the dayside to the nightside of the earth, but from magnetic data no certain conclusion has been reached as to how the current circuit is closed." As described earlier, the closure of the ionospheric currents became the source of intense debate, with Sydney Chapman and his colleagues favoring closure completely within the ionosphere and Alfvén adopting Birkeland's suggestion of field-aligned currents. Alfvén understood the unwillingness to accept Birkeland's ideas and stated them clearly in his book [14] on page 177: "The main objections against Birkeland–Störmer's theory are the following. Electrons moving in Störmer orbits

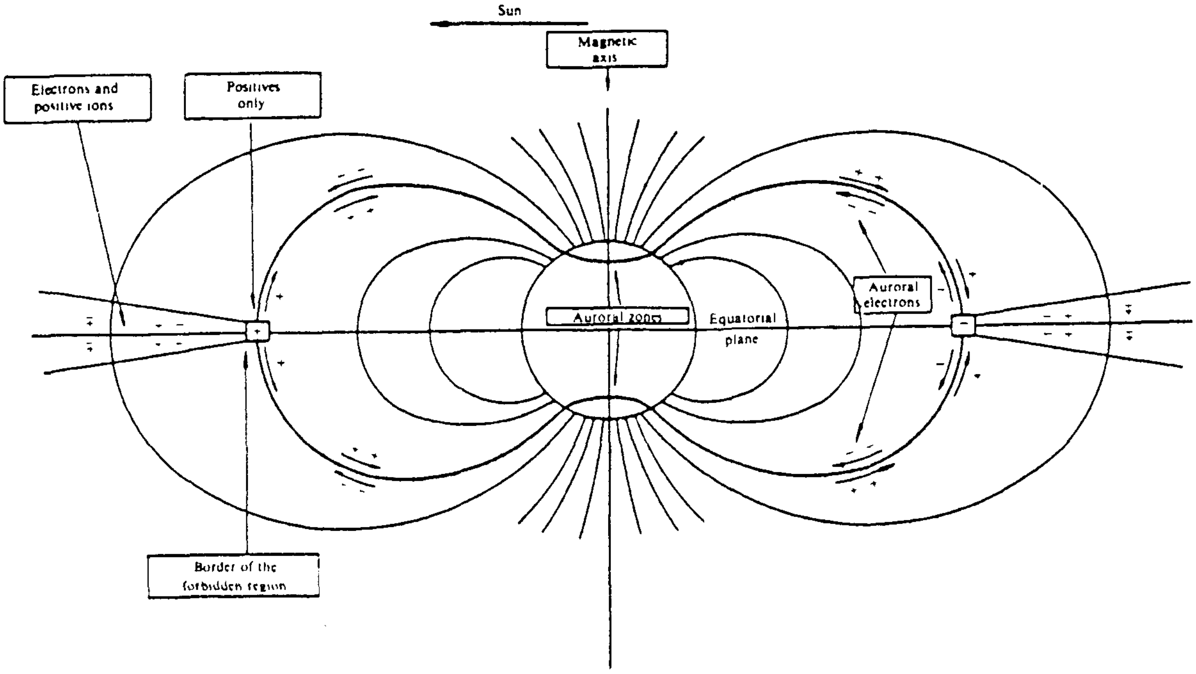

Fig. 3. The system of field-aligned currents proposed by Alfvén [11].

would hit the earth at the polar distance (~ 22°) of the auroral zone if their energy were of the order of 10^8 eV. The penetration power calculated from the minimum height of the aurora (80–100 km) indicates, however, that the energy is only 10^4–10^5 eV. Electrons with this energy would reach the earth only one or two degrees from the poles. Further, the theory does not take account of the solar magnetic field, which in fact had not been discovered in Birkeland's time.... Finally, as first pointed out by Schuster, electrically charged particles of one sign would cause a prohibitively large space-charge if transmitted in sufficient number to cause terrestrial disturbances of the order of magnitude observed. This is a special case of the general rule that in cosmic physics the number of positive particles per unit volume must approximately equal the number of negative particles. The conclusion is that the agent responsible for magnetic storms and aurorae must be a cloud which contains approximately the same amount of positive as of negative charge. Strong arguments in favor of this opinion have been given by Chapman and Ferraro [16, 17] and by Chapman and Bartels [1]. The cloud probably consists of ionized atoms." Alfvén recognized that Birkeland's currents could not be directly connected to the Sun. He believed that the Sun's magnetic field would play an important role in Solar-Terrestrial Connections, and supported Chapman and Ferraro's idea that neutral ion clouds emitted from the sun were responsible for magnetic storms. We now know that this ion cloud is emitted on a permanent basis from the Sun, and it is referred to as the "solar wind."

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 contained in the ionosphere from a study of surface magnetic field measurements according to Fukushima [18]. The absolute proof of Birkeland's field-aligned currents could only come from observations above the ionosphere with satellites. The first evidence for the existence of field-aligned currents came in 1966. A magnetometer on board a U.S. Navy navigation satellite launched in 1963 recorded magnetic field disturbances on nearly every pass over the high-latitude region of the Earth. The magnetic disturbances were originally interpreted as hydromagnetic waves by Zmuda and his colleagues [19]. But it was soon realized that their latitude extent was too small for waves of the appropriate wave-length, and they were interpreted as being due to field-aligned or Birkeland currents by Cummings and Dessler [20].

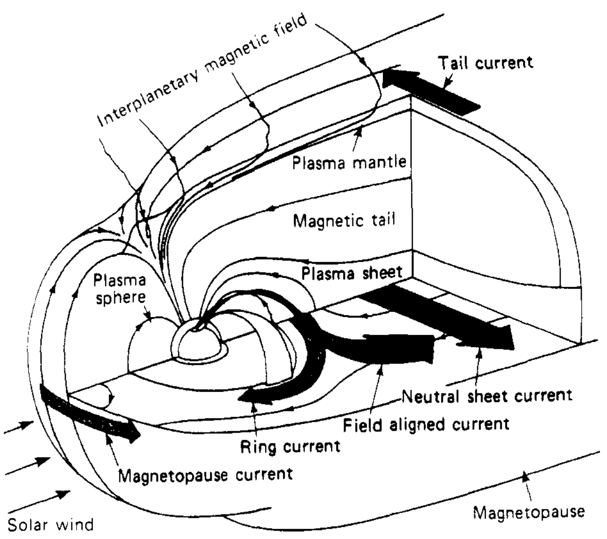

Fig. 4. The Earth's magnetosphere with the various current systems that flow in this complicated plasma laboratory.

3. Satellite observations of Birkeland currents

An enormous amount of work has been conducted on Birkeland currents in recent years with ground-based and satellite observations, computer simulations, and theoretical investigations (see the reviews by Mauk and Zanetti [21]; Potemra and Fukushima [22]; Friis-Christensen and Lassen [23]; Iijima [24]; Potemra [25–27].

The most common method of detecting currents has been by

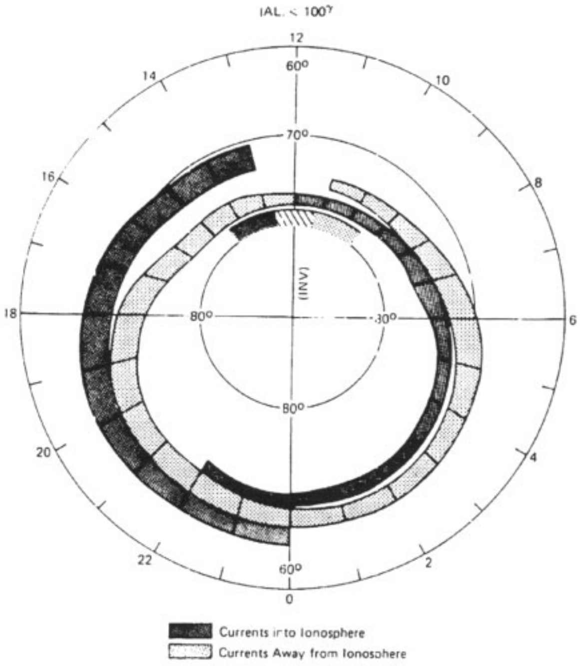

Fig. 5. The distribution and flow directions of large-scale Birkeland currents determined by Iijima and Potemra [29] from 493 passes of the Triad satellite.

virtue of the magnetic perturbations they produce. A satellite can pass through a field-aligned current and measure the *in situ* magnetic perturbations. The intensity and flow direction of the current is deduced from the formula $J = 1/\mu_0$ curl $\boldsymbol{B}$, where $\boldsymbol{B}$ is the measured perturbation transverse to the geomagnetic field. This technique requires certain assumptions to evaluate, because it is not possible to determine the three-dimensional "curl" from a single satellite pass. Furthermore, all transverse magnetic disturbances may not be caused by stationary field-aligned currents, because Alfvén waves also produce magnetic perturbations. It has been usually argued that the large-scale magnetic perturbations (100nT or larger observed over distances larger than 50 km in the low-altitude ionosphere) can be explained reasonably in terms of large-scale Birkeland currents. Furthermore, the patterns of large-scale Birkeland currents deduced in this manner are supported by observations of precipitating particle patterns, and by measurements of large-scale convection electric field patterns [28].

If the "infinite current sheet" approximation is adopted [5,28] the integrated sheet current intensity, $\int \boldsymbol{J}\,dl$, is related directly to the amplitude of the magnetic disturbance, ΔB, since $\int \boldsymbol{J}\,dl = 1/\mu_0 \Delta B$. A 100nT disturbance corresponds to a sheet current intensity of 0.08A/m. A 100nT variation over a distance to 100km is equivalent to a Birkeland current density of 0.8 μA/m^2.

Large-scale Birkeland currents are concentrated in two principal areas that encircle the geometric pole. Figure 5 is a summary of the average spatial distribution in the northern high-latitude region determined from hundreds of satellite orbits analyzed by Iijima and Potemra [28]. The Birkeland current flow patterns have been arbitrarily designated 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, whereas the region 2 currents flow in the opposite direction at any given local time. The basic flow pattern of Birkeland currents remains unchanged over a wide range of geomagnetic conditions, and the regions widen and shift to lower latitudes during disturbed periods. The distinctive pattern of Birkeland currents near noon are closely related to the orientation and amplitude of the interplanetary magnetic field, IMF (confirming the importance of the Sun's magnetic field suggested by Alfvén). The Birkeland currents near midnight strongly depend on geomagnetic activity and phases of substorms.

The local time distributions of large-scale Birkeland currents are important because they can be used with geomagnetic field mapping techniques to investigate the magnetospheric projections of a particular current segment. Patterns of particle precipitation can be used to verify these projections. The magnetospheric projection of the Birkeland currents provides information on the ultimate sources of the currents. The continuous bands of Birkeland currents depicted in the polar plot of Fig. 5 are due to the superposition of field-aligned currents driven by at least a half-dozen different sources located at widely separated regions of the magnetosphere. The six major categories of Birkeland can be specified as follows [27]:

(1) Region 2 at all local times, except near midnight.
(2) Region 1 on the dayside, except at noon.
(3) Region 1 on the nightside, except at midnight.
(4) The noon system.
(5) The midnight system.
(6) The polar cap NBZ (northward IMF) system.

The characteristics of these currents are discussed in detail in my review of Birkeland currents [27] and their sources are summarized as follows:

- Region 2 currents: This system is connected directly to the ring current which is driven by plasma pressure gradients within the magnetosphere.
- Dayside region 1 (except at noon): This system is the most intense part of the total region 1 system (2/3 to 3/4 of the total magnitude of all region 1 currents) and maps to the low-latitude boundary layer (LLBL) where viscous and pressure gradient sources are available to drive these currents. Their magnitudes increase as B_z becomes more negative. This system is insensitive to changes in B_y.
- Nightside region 1 (except at midnight): This system maps to the plasma sheet, topologically connected to the LLBL. Processes in the plasma sheet drives 1/4 to 1/3 of the total region 1 current intensity.
- **Noon Birkeland currents.** This system is intimately related to the processes modulated by the IMF, which regulates the flow of solar wind plasma into the magnetosphere. The system occurs in oppositely directed pairs of currents. They are sometimes confused with, but are distinctly different from region 1 currents at other local times. This pair of currents is adequately accounted for by the inertial current driven by plasma motion near noon.
- Midnight Birkeland currents: This system, which vanishes during periods of extreme quiet, results from complicated processes associated with substorms.
- NBZ currents: This system occupies nearly the entire polar region and becomes more intense when B_z increases (i.e. the IMF has a strong northward component). The flow directions of the NBZ currents are the same as the noon mantel currents (the poleward system of the noon pair of currents described above), which occur during negative B_z periods (southward IMF).

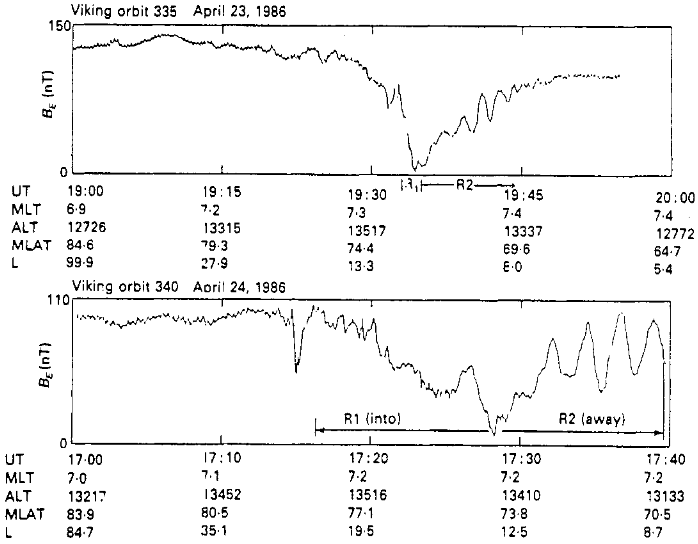

Fig. 6. Magnetic field disturbances in the eastward geomagnetic field component measured by Viking near its apogee. Regions of large-scale region 1 and region 2 Birkeland currents are labelled. The oscillations superimposed upon the region 2 currents are Alfvén waves.

4. Satellite observations of Alfvén waves

Observations of oscillations in the geomagnetic field date back to the beginning of the century. Birkeland [29] is credited as being the first to report magnetic field oscillations later called "giant pulsations" [30]. Dungey [31, 32] was one of the first to discuss these variations in terms of resonant oscillations in the geomagnetic field, and Sugiura and Wilson [33] extended the "elastic string model" of Alfvén [14] to study geomagnetic field oscillations in the auroral zone with amplitudes of several hundred 100 nT and periods ranging from 4 to 8 min. Lam and Rostoker [34] used data from a meridian chain of surface magnetometers to study Pc 5 micropulsations in the morning sector. They found that the Pc 5 activity maximizes within the same latitudinal range occupied by the westward electrojet. Poulter et al. [35] expanded on Lam and Rostoker's work and suggested that the Pc 5 pulsations ought to be expected near the large-scale Birkeland current system because the auroral electrojet is approximately coincident with the region 1 and 2 currents. Poulter et al. combined magnetic field observations from the TRIAD satellite with pulsation electric fields in the ionosphere measured with the Scandinavian Twin Auroral Radar Experiment (STARE) radar. They identified a 400-s period wave in the STARE electric field as a toroidal mode field line resonance and were able to associate the latitudinal amplitude and phase variation with Birkeland currents inferred from the TRIAD data.

There have been many reports of low-frequency oscillations in the geomagnetic field observed with satellites. These include the ATS 1 observations in the equatorial plane at 6.6 Re by Cummings et al. [36]. These authors developed a theory to explain the oscillations with periods from 50 to 300 s as standing Alfvén waves in the magnetosphere. They computed the theoretical eigen periods for the uncoupled toroidal and poloidal wave modes associated with an external dipole magnetic field for the Earth, which they took as a perfect conductor. Observations acquired by the DODGE satellite in an equatorial circular orbit at 6.26 Re showed transverse magnetic field oscillations with periods between 3 and 240 s [37]. Patel and Cahill [38] and Patel [39] reported observations of hydromagnetic waves in the magnetosphere between 7 and 10 Re with Explorer 12.

Magnetic field oscillations near L = 4.5 were studied at conjugate ground observatories near Siple, Antarctica, and Roberval, Canada, and in space with the DE 1 satellite by Cahill et al. [40]. These were obtained during a large geomagnetic storm, and the authors interpreted the 180 s and 240 s magnetic pulsations as fundamental, toroidal, resonant oscillations of a field shell. From a comparison of electric and magnetic oscillations measured by DE 1 during this event, Cahill et al. determined that the electric field variations lead the magnetic variations by 90°, which is the correct relationship for the fundamental harmonic mode [41]. Electric and magnetic field observations obtained by DE 1 were also used to study 20-to 300 s pulsations in the L = 2.8 to 9.7 and 0770 to 1300 MLT region by Cahill et al. [42]. They confirmed that the electric field variations lead the magnetic variations by about 90° and that the frequency of pulsations decreases with increasing L.

Engebretson et al. [43] studied magnetic field observations from the AMPTE CCE satellite (in an 8.8Re apogee equatorial orbit) and showed that there is a frequent occurrence of harmonically structured, azimuthally polarized pulsations in the outer magnetosphere during daytime hours. They also found that the frequencies of these pulsations decreased with increasing radial distance from the Earth, and they interpreted them as independent resonances of local magnetic flux tubes. The AMPTE CCE and Viking satellites provided an opportunity to observe the same type of harmonic, azimuthally polarized, ULF pulsations at two widely separated points along a flux tube [44]. The frequencies and relative amplitudes along the field line supported recent theories of multiple field line resonances of Alfvén waves developed, for example, by Allan and Knox [45].

A statistical study of Pc 3–5 (10- to 600 s period) pulsations was conducted with data acquired by the magnetic field experiment on the AMPTE/CCE satellite [46]. The CCE orbit is equatorial (4.8° nominal inclination with apogee at 8.8 Re and perigee at 1,000 km altitude and a period of 15.6 hours). The range of magnetic latitude covered was ±16°, and the orbit precessed westward at a rate of 0.77° per day. More than 7,200 hours of magnetic field data were compiled at all local times for L in the range 5 to 9. The pulsations were classified in nine categories by spectral type, approximate polarization, spectral intensity, and satellite location. Harmonic toroidal resonances were found to be the dominant coherent activity on the dayside, particularly on the prenoon hours, where they occur 60% of the time. Fundamental toroidal resonances were observed 80% of the time for magnetic latitudes above 13° in the dawn sector. Consequently, toroidal resonances are a common feature of the dayside magnetosphere.

Considering Sweden's heritage and contributions to the understanding of auroral and space plasma physics it was appropriate that their first satellite would be developed for the purpose of investigating the plasma environment of the Earth. Sweden's first satellite, called Viking, was launched on February 21, 1986, into a polar 187 km by 3.1 Re orbit, and carried instruments to measure magnetic and electric fields, hot plasmas, plasma waves, and UV images of the aurora [47]. Viking provided a new perspective for measuring geomagnetic field oscillations (Alfvén waves) and Birkeland currents in the magnetosphere. The geomagnetic field geometry and Viking's low speed near apogee allowed the satellite to cross L shells at a much lower rate in the high-latitude regions than could previous satellites except for DE 1. Therefore, magnetic field oscillations with periods as long as a few minutes could be observed with Viking's magnetic field experiment. Some examples of Viking's observations of Alfvén waves that occur on geomagnetic field lines that guide Birkeland currents are provided in the following.

Figure 6 shows the geomagnetic eastward components of magnetic field measured by Viking on April 23 and 24, 1986, when the satellite was near its apogee over the morning auroral zone (near 0700 ML). The data acquired on April 23, 1986, show a steep negative (westward) gradient beginning approximately at 19:31 UT. This is interpreted as a downward flowing Birkeland current with a density of 0.4 μA/m^2. A positive (westward) gradient in the magnetic field is seen after 19:35 UT which is interpreted as an upward flowing region 2 Birkeland current. Superimposed upon this positive gradient are oscillations with amplitudes up to 38 nT and periods of about 1.5 min. The data acquired on April 24, 1986, show a very wide downward-flowing Birkeland current extending from about 17:15 to 17:27 UT (40° of latitude) with a density of about 0.06 μA/m^2. A positive (eastward) gradient is evident at lower latitudes, but this is nearly hidden by the large oscillations in the field. The density of this upward flowing Birkelend current is about 0.03 μA/m^2 and the oscillations superimposed upon it have amplitudes up to 60 nT with a period of about 2 min (frequency of about 8 mHz). Observations of electric fields acquired by Viking at the same time (not shown here but can be seen in Plate 3 of Potemra et al. [48]) show the same periodic variation as the magnetic fields, but delayed in phase by almost a quarter-period. This is the appropriate phase relationship for the fundamental mode of the toroidal standing wave oscillation of the geomagnetic field, also called an Alfvén wave. The Viking results have provided some of the first evidence for the occurrence of Alfvén waves on field lines that guide Birkeland currents.

5. Conclusion

Birkeland currents and Alfvén waves are fundamental to an understanding of the Earth's plasma environment. Hannes Alfvén was very proud of the contributions that international space programs, especially Viking, had made to the understanding of a variety of phenomena including magnetospheric currents, waves, and double layers [49].

It is hard to think of a scientific discussion among space physicists that does not include Alfvén's name in some way. It is difficult to find a paper on space plasma physics that does not reference some principle developed by Alfvén and named after him. And it is almost impossible to imagine the present state of Space Physics without the legacy provided by Hannes Alfvén.

Acknowledgements

The work reported here has been supported by the U.S. Office of Naval Research, the National Science Foundation, and the National Aeronautics Administration.

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