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Kristian Birkeland: *The first space scientist*

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ABSTRACT

More than one hundred years ago Kristian Birkeland (1867–1917) first addressed the question as to why auroras appear overhead when the Earth's magnetic field is disturbed. He laid foundations for our current understanding of geomagnetism and polar auroras. For the first time cosmic phenomena were scaled and simulated in a laboratory. Birkeland's terrella experiments were ingenious. Even though the famous Lord Kelvin, in 1892, wrote that no matter passes between the Sun and the Earth, Birkeland's first auroral theory from 1896 is based on charged particle of solar origin, illustrated by the following quotation: "the auroras are formed by corpuscular rays drawn in from space, and coming from the sun". Thus, the year 1896 marks the founding of space plasma physics. His most enduring contribution to auroral physics was his recognition that field-aligned currents are needed to couple auroral phenomena in the upper atmosphere to interplanetary space. The existence of field-aligned currents was controversial and disputed vigorously among scientists for more than 50 years. During *The Birkeland Symposium* in 1967 it was unanimously proposed that field-aligned currents in space should be called "Birkeland currents", which was accepted by the International Union for Geomagnetism and Aeronomy. Today, plasma physicists strongly believe that many significant cosmic phenomena result from streams of Birkeland currents.

1. A brief biography of the scientist Birkeland

Our lives pass within confines that are brief in time and limited in range. There are, however, people whose contributions to collective human experience extend beyond their prescribed times and places. I place before readers of this journal a synopsis of the life and contributions of such a man, Olaf Kristian Bernhard Birkeland, a Professor of Physics at The Royal Frederik University in Kristiania, the capital of Norway, close to the beginning of the 20th century. (In 1925 Norway's capital reverted to Oslo, its name before the devastating fire in 1624.) The subtitle *The First Space Scientist* places Birkeland's life in the context of space exploration, half a century before "Sputnik" and "Apollo" entered our vocabulary (Fig. 1).

Birkeland was born in Kristiania on December 13, 1867, and died in Tokyo on June 15, 1917. In publications after 1898 he simply referred to himself as Kr. Birkeland. His life spans a watershed period when insights about electricity and magnetism, codified by Maxwell in the mid-19th century, evolved from theoretical curiosities to become the basis for electronic technology and eventually for our understanding of the geospace environment.

Before finishing high school at the age of 18, he wrote the paper "Une Méthode Énuméractive de la Géométrie". Thus, early on he showed a keen interest in both mathematic and physical science. In June 1890, Birkeland completed university studies in physics, graduating youngest in his class with the highest grades. In January 1893 he was awarded a *universitetsstipendiat*, equivalent to a Research Assistantship, at the University of Kristiania. Much of his early research was conducted in France, Switzerland and Germany between January 1893 and August 1895. During this period Birkeland published two theoretical papers that drew wide attention. His mathematical training in Norway provided a superb foundation for developing the first general solution of Maxwell's equations and energy transfer by means of electromagnetic waves (Fig. 2) (Birkeland, 1895). He continued to investigate the properties of electromagnetic waves in conductors and wave propagation through space. During the years 1895–1913, his primary research was in studies of geomagnetic disturbances, auroras, solar–terrestrial relations and cosmology. He was the first to stress a critical role for electromagnetic forces in cosmos.

Birkeland was a gifted man with a wonderfully inventive mind that bubbled with ideas and sought to investigate every aspect of the physical sciences. At the age of 28, he was elected member of the Norwegian Academy for Science and Letters. In the Academy's 150-year long history only the famous Arctic explorer and oceanographer Fridtjof Nansen (1861–1930) was elected at a younger age. In October 1898, Birkeland was called by King Oscar II

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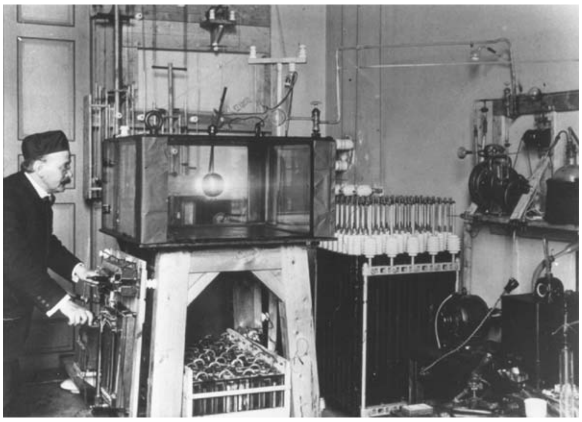
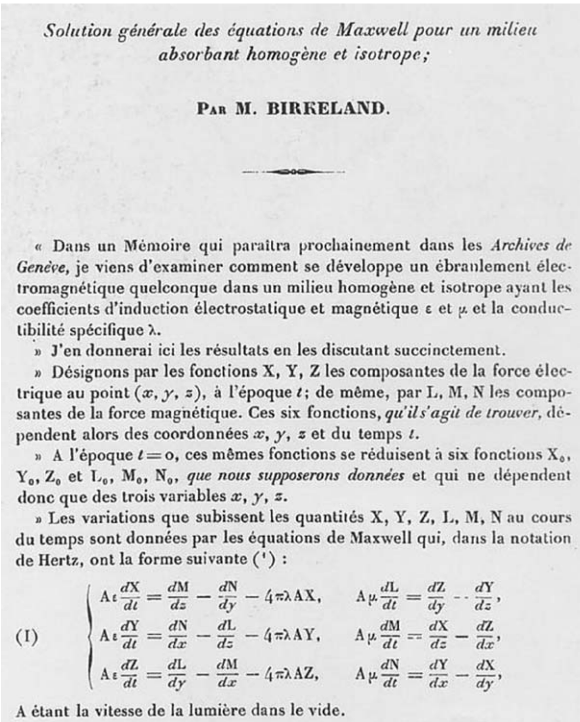


Fig. 1. A picture of Kristian Birkeland in his terrella-laboratory from around 1910. He carried out many different auroral simulations.



Solution générale des équations de Maxwell pour un milieu absorbant homogène et isotrope;

PAR M. BIRKELAND.

« Dans un Mémoire qui paraîtra prochainement dans les *Archives de Genève*, je viens d'examiner comment se développe un ébranlement électromagnétique quelconque dans un milieu homogène et isotrope ayant les coefficients d'induction électrostatique et magnétique ε et μ et la conductibilité spécifique λ.

» J'en donnerai ici les résultats en les discutant succinctement.

» Désignons par les fonctions X, Y, Z les composantes de la force électrique au point (x, y, z), à l'époque t; de même, par L, M, N les composantes de la force magnétique. Ces six fonctions, *qu'il s'agit de trouver*, dépendent alors des coordonnées x, y, z et du temps t.

» A l'époque $t = 0$, ces mêmes fonctions se réduisent à six fonctions X_0, Y_0, Z_0 et L_0, M_0, N_0, *que nous supposerons données* et qui ne dépendent donc que des trois variables x, y, z.

» Les variations que subissent les quantités X, Y, Z, L, M, N au cours du temps sont données par les équations de Maxwell qui, dans la notation de Hertz, ont la forme suivante (¹) :

$$(\mathrm{I})\quad \left\{\begin{array}{ll} A\varepsilon\frac{dX}{dt} = \frac{dM}{dz} - \frac{dN}{dy} - 4\pi\lambda AX, & A\mu\frac{dL}{dt} = \frac{dZ}{dy} - \frac{dY}{dz}, \\ A\varepsilon\frac{dY}{dt} = \frac{dN}{dx} - \frac{dL}{dz} - 4\pi\lambda AY, & A\mu\frac{dM}{dt} = \frac{dX}{dz} - \frac{dZ}{dx}, \\ A\varepsilon\frac{dZ}{dt} = \frac{dL}{dy} - \frac{dM}{dx} - 4\pi\lambda AZ, & A\mu\frac{dN}{dt} = \frac{dY}{dx} - \frac{dX}{dy}, \end{array}\right.$$

A étant la vitesse de la lumière dans le vide.

Fig. 2. The first page from Birkeland's 1895 paper in Comptes Rendus where he derived the first general solution of Maxwell's equations.

of Sweden to be senior Professor of Physics at the University of Kristiania. At that time he was the youngest professor on the faculty. Because he looked younger than his age, for several years he was called "the boy professor". In 1906 he was elected a fellow at the Faraday Society of London and in 1908 received an honorary doctorate, *Doktor Ingenieur Honoris Causa*, from the Dresden Technical University in Germany (Egeland and Burke, 2005).

2. Birkeland's laboratory simulations

While Professor of Physics at The University in Kristiania (1898–1917), Birkeland laid foundations for our current understanding of geomagnetism and polar auroras. In 1901 Birkeland initiated a new set of laboratory simulations that he called *Terrella Experiments*. He hoped to prove incontrovertibly the correctness of his theoretical interpretation of auroral and geomagnetic disturbances. For the first time cosmic phenomena were scaled and simulated in a laboratory. His terrella experiments were at once simple and ingenious. His largest chamber was a full cubic meter in volume. He fully believed that the laboratory simulations confirmed his understanding of auroras. They opened new paths, suggesting how electromagnetic forces might operate in the solar system. Birkeland's laboratory simulations were brilliant successes that allowed him to argue by analogy to the causes of auroras and geomagnetic disturbances. In 1899, Birkeland built the first permanent auroral observatory in northern Norway atop a 900-m mountain. He conducted three auroral and geomagnetic expeditions between 1897 and 1903. Of these, his four-station polar expedition during the winter of 1902–1903 was the most important (Alfvèn and Egeland, 1987).

After 1906, Birkeland extended his terrella experiments and applied the electromagnetic theory to include solar and cosmic phenomena. His simulations of the influence on corpuscular radiation from the Sun, on Saturn's ring, and comets tails are fascinating, especially coming at a time when other scientists maintained that the Earth was surrounded by vacuum. His concepts of stars as sources of matter for interstellar space and the importance of electromagnetic forces throughout the cosmos are markedly less known. His theoretical proposals were rooted in laboratory experiments designed to simulate space interactions. Birkeland blended a unique intuition with talent for technical work. His approach generated fruitful frameworks for understanding basic plasma processes.

Much of Birkeland's story concerns hard-won observations and bold interpretations of the natural interactions between the Sun and the Earth's magnetic field that produce auroral displays and geomagnetic storms. He distinguished himself from contemporary investigators through laboratory simulations of natural electrical phenomena. Far ahead of his time, Birkeland's prophetic concepts about the electric particles and currents controlling the physics of space passed into decades of eclipse before re-emerging in the 1970s. Birkeland's reputation remained strong in Scandinavia, although heated debates raged concerning the validity of his speculations about space. Even in principle, no resolution could be found before spacecraft probed altitudes above 100 km.

Birkeland based the main part of the physical interpretation on his advanced laboratory simulations and daring campaigns in the Arctic wilderness in the light of Maxwell's discovered laws of electricity and magnetism. He uncovered hidden treasures in solar–terrestrial couplings and introduced many ideas that still remain central to these fields. Although much of Birkeland's results and ideas were unrecognized or dismissed for decades, he became vindicated when satellites could fly above the Earth's atmosphere.

To understand Birkeland's accomplishments and the arguments against them, we must set aside the technological world we take for granted and imagine ourselves at the end of the 19th century. We must continually ask, "What did scientists of the time know?" For example, although Birkeland began working with "cathode rays" in 1894, it was not until 1897 that Joseph John Thomson (1856–1940) identified them as the electrical corpuscles we now call electrons (Thomson, 1897).

There is also a problem of language. The 19th and early 20th centuries were times of singular growth in scientific understanding. Standard terminology, mathematical notation and physical units have now evolved that allow readers access to the thoughts of American, European or Asian scientists without requiring mental gymnastics to map between them. However, reaching this stage of synthesis required the unification of partially described phenomena and diverse metaphors into a common nomenclature. Like any explorer Birkeland had to invent new language as his research uncovered new layers of physics.

Birkeland was the complete scientist, a gifted theorist, as well as an imaginative laboratory and field experimentalist. He devised laboratory experiments that, for their time, were of unprecedented size and complexity, and he made them work. Many studies have been made of eminent scientists. Some scholars are purposeful, follow straight lines toward their goals and never allow interruptions or distractions. Others take a different approach. Like gardeners who develop hybrid roses, they try many different methods and techniques with varying degrees of success. Birkeland belongs to this latter category. Birkeland's reputation survived and flourished because he was the first to forge alliances between science and the Norwegian government to investigate space, and between science and international industry to resolve an emerging crisis in feeding the growing global population.

3. Technology and applied physics

From 1901 to 1906 Birkeland turned to applied physics and technological development. His primary motive for engaging in this activity was to generate the funds needed to support ambitious research projects and to build a modern research laboratory whose cost greatly exceeded what the University could afford. All together Birkeland developed 60 patents in 10 different subject areas. In one field, the production of agricultural fertilizers, he earned large sums of money. Birkeland invented the plasma arc leading to the Birkeland–Eyde method for industrial nitrogen fixation, and the founding of Norsk Hydro that today remains one of Norway's largest industrial enterprises (Fig. 3). While Norwegians mostly remember him for his leading role establishing Norsk Hydro, Birkeland viewed the effort as a diversionary episode in his life.

Birkeland's first patent concerned an electromagnetic cannon that is similar in concept to a rail gun. He then formed his first company called Birkeland's Firearm. A modern rail gun was used to simulate how the Space Shuttle Columbia's left wing was breached by a high-speed packet of foam (Egeland, 1989). Birkeland also held patents related to electrical switches and even formed a small company for their industrial production. He also took out patents related to hardening whale oil to produce margarine, electromagnetic devices to probe for metals and minerals, the refining of oil, and mechanical hearing aids. In 1906, Birkeland applied for funds from international financiers in Stockholm via the Wallenberg family to support research for utilizing atomic energy; in 1915, he sought support to built automated meteorological stations to improve severe weather predictions. From 1908 to 1910 he conducted extensive radio-wave experiments related to telegraph and telephone technology. To help improve radio communications capabilities, at his own expense, Birkeland erected a 15-m high transmitter antenna on the roof of the University's main building and built receiving stations a few miles away.

Birkeland invested more and more money earned from industrial inventions to support his many projects in scientific research.

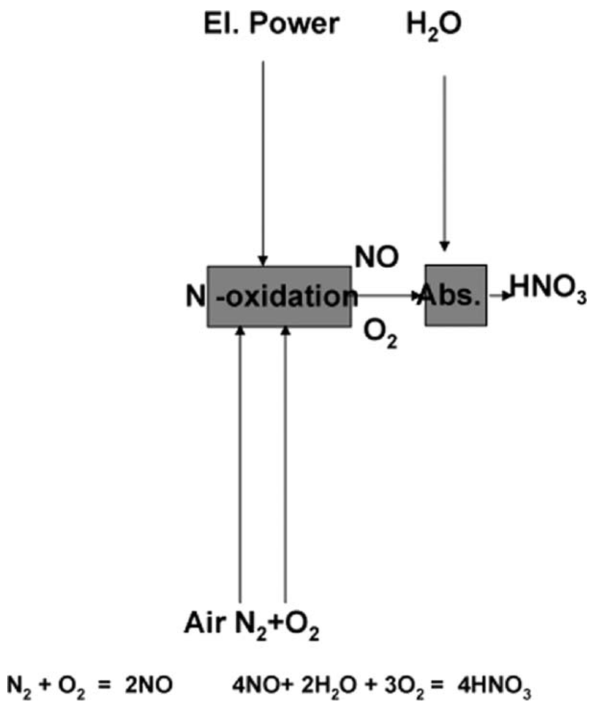


Fig. 3. A block diagram showing the principle to the Birkeland–Eyde method for industrial nitrogen fixation.

4. Birkeland currents and electric currents in the upper atmosphere

One of Birkeland's most enduring contributions to solar–terrestrial research was his recognition that field-aligned currents are needed to couple geomagnetic and auroral phenomena in the upper atmosphere to interplanetary space and the Sun. Considering his early work with Maxwell's equations and his advanced laboratory simulations, it is not surprising that Birkeland already in 1899 was convinced that electric current flowing in the upper atmosphere must be the main cause for the observed geomagnetic disturbances.

In the analysis of the geomagnetic records – in his book *Résultats des recherches magnéthiques faites par l'expedition Norégienne de 1899–1900* from 1901 – the direction and intensity of the current responsible for the disturbances observed were marked on world maps. Then he clearly saw that the magnetic perturbations were at right angles to the causative currents. It was from this type of analysis that he discovered the strong east–west auroral "electrojet" with currents up to million amperes (Birkeland, 1901).

He argued that terrestrial phenomena associated with auroral emissions are best described in a coordinate system that is fixed with respect to the Sun. He then constructed the first "two-cell global pattern" of atmospheric currents that converge over the polar region, based on ground magnetic field measurements (Fig. 4). Modern satellite-based measurements of electric fields confirm the existence of such two-cell patterns. These patterns are critical for understanding how electromagnetic energy from the Sun disturbs the high-latitude upper atmosphere.

Around 1900 – shortly after the electron had been identified as an independent and fundamental unit of charge – Birkeland understood that these currents could be derived from two possible sources. In his major scientific contribution "*The Norwegian Aurora Polaris Expedition 1902–1903"(NAPE)*—a monumental two-volume monograph published separately in 1908 and 1913 he wrote in NAPE, Section 36 (Birkeland, 1908 and 1913):

"With regard to the future course of the current, there are two possibilities.

1. The entire current system belongs to the Earth. The current-lines … flow at some height above the Earth.

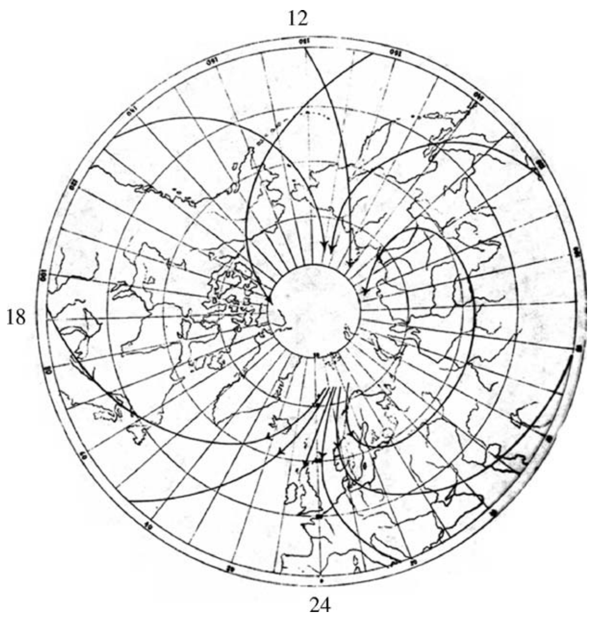


Fig. 4. Current patterns viewed from above the North Pole. The global ionospheric currents are represented in a coordinate system oriented with respect to the Sun. In a 24-h period, the Earth rotates under the current pattern, as indicated by the curved lines (Birkeland, 1901). The Earth's upper atmosphere is today called the ionosphere, but the ionosphere was first discovered by Appleton, two decades later – around 1930.

2. The current is maintained by a constant supply of electricity from without. The currents will consist principally of vertical portions. At some distance from the Earth's surface, the current from above will turn and continue for some time in an almost horizontal direction, and then either once more leave the Earth, or become partially absorbed by the atmosphere".

That Birkeland as an explanation of polar elementary storms (today called substorms) favoured field-aligned currents is clear from NAPE, Section 92 where he wrote:

"We consider it to be beyond doubt that the powerful storms in the northern regions, that we have called elementary, are due to the action of electric currents near the auroral zone".

Thus, strong electric currents flowing overhead in the auroral zone produced the observed magnetic disturbances. The important point for Birkeland was now that these horizontal currents were connected to currents along the Earth's magnetic field that flow into and out of the upper atmosphere near the equatorward and pole ward boundaries of the auroral electrojet-current.

Some of Birkeland's original sketches of field-aligned currents in NAPE from 1908 – for explanations of the negative polar elementary storms – published in the section called "On the cause of magnetic storms and the origin of terrestrial magnetism", are shown in Fig. 5.

As the first to examine disturbance records from around the globe during magnetic storms, Birkeland estimated that currents up to one million amperes must flow in the upper atmosphere. He understood intuitively that only the Sun could drive and sustain such large electrical currents. Consequently, currents in the upper atmosphere must connect to generators in deep space via magnetically field-aligned currents. Indeed, Birkeland found the predicted currents replicated in laboratory simulations. He estimated that the current flowed at an altitude above 100 km. This fits well with present day estimates of the auroral electrojet to be in the range between 0.3 and 5 million amperes.

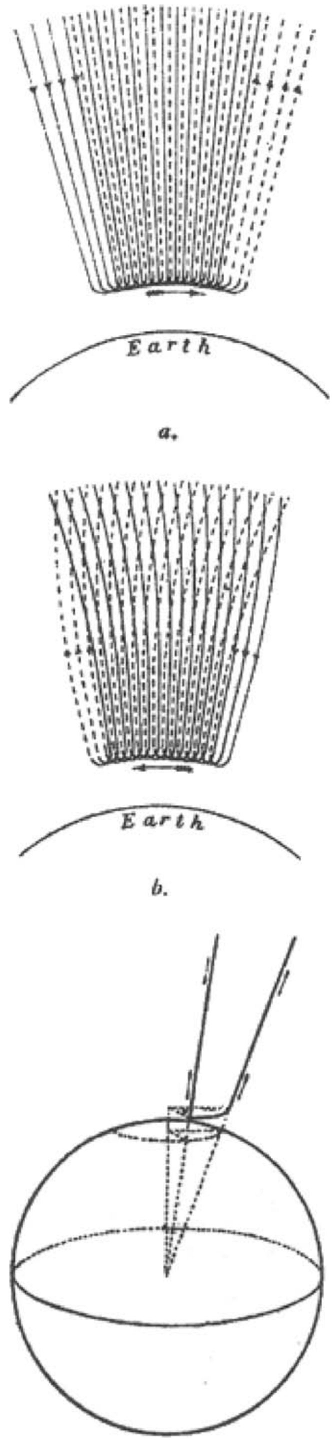


Fig. 5. Original field-aligned current systems suggested by Birkeland. These figures are from his main scientific monograph in 1908.

Given the intensity of currents needed to explain the observed magnetic disturbances, Birkeland concluded that only the Sun could provide the electromagnetic forces needed to power magnetic storms and auroral emissions.

Birkeland's conclusion that field-aligned currents couple geomagnetic phenomena to interplanetary space has profound and far-reaching significance for understanding the origin of auroras and geomagnetic currents.

The first direct evidence of the existence of field-aligned currents was found in 1966 measurements by a US Navy TRIAD satellite (Potemra, 1989). A year later the International Union for Geomagnetism and Aeronomy declared that they should be called "Birkeland currents".

5. Controversies regarding field-aligned currents

The most common method used to detect the presence of currents in the polar ionosphere is through the magnetic perturbations they produced on the ground. However, a quirk of nature actually makes it impossible using only ground-based magnetic field measurements to judge unambiguously between current systems that contain field-aligned segments and those that completely close in the ionosphere. That was pointed out by professor Naoshi Fukushima (1920–2003) in his 1989 paper (Fukushima, 1989). Inferring the real current pattern required magnetic field measurements in space.

The existence of field-aligned currents was disputed vigorously among scientists for over 50 years. British scientists, headed by the eminent mathematician and scientist Sydney Chapman (1888–1970) and his many co-workers – referred to as *the British School* – were critical to Birkeland's work in general and particularly critical to field-aligned currents. They concluded that all ground geomagnetic disturbances could be explained by "equivalent" current patterns, completely closed within the ionosphere. No field-aligned currents were needed (Chapman, 1968).

Before Chapman started his research, British scientists largely ignored Birkeland's analysis of geomagnetic disturbances because they found it impossible to believe that the Sun was the ultimate source of auroral and geomagnetic activity. In 1892 William Thomson (1824–1907), better known as Lord Kelvin, expressed his opinion that no matter passes between the Sun and the Earth. In spite of mounting evidence to the contrary, Kelvin's opinion was definitively rejected only after satellites had passed though the boundary of the Earth's magnetic field into the solar wind. Although Birkeland was aware of the early objections, he found his terrella simulations of auroras so compelling that he stood by his initial hypothesis calling for direct impacts by solar particles.

Chapman introduced a number of important theoretical concepts in contemporary magnetospheric and ionospheric physics. He approximated the overhead currents as flowing horizontally in the ionosphere. From this perspective he diligently denounced Birkeland's work and ideas and followed the equivalent-current system method.

His vantage point was distinctly different from Birkeland's. Instead of focusing on individual events, Chapman tried to find an average morphology of magnetic disturbances from their statistical means. They concluded that the average characteristics of magnetic disturbances did not differ substantially from those of very large storms. Their thinking dominated magnetic storm studies up to the space age and argued that the Birkeland current system is inadequate. From his perspective he diligently denounced Birkeland's work and ideas and followed the hypothetical, equivalent-current system method and concluded, "Birkeland's current system should be disregarded as unsatisfactory".

That field-aligned currents was controversial and vigorously disputed even in the 1960s is demonstrated by the following quotation from Chapman's 1968 paper: "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 aurora and magnetic storms". Unfortunately, the British School misrepresentation of the Birkeland current system was not discovered until 1964 by professor Naoshi Fukushima. He found the serious flaw of their S_D current system with their interpretation of Birkeland's (cf. Fukushima, 1989 and Fig. 6).

Fukushima showed that they should have compared the two proposed current systems with the same electrojet configuration along the auroral zone, but the damage was done. Birkeland's explanation of magnetic storms was neglected for nearly 30 years. Fortunately, Hannes Alfvén (1908–1989) – the Nobel Laureate in Physics – together with professor Alexander J. Dessler, greatly admired Birkeland's work and became an unyielding champion in opposition to the British school. Dessler (1983) had described the first recognition of field-aligned currents. Together with several Japanese scientists, they argued strongly for the necessity of field-aligned electric currents for understanding both geomagnetic disturbances and auroras. Both the detection and the identification of magnetic perturbations caused by field-aligned currents appear in retrospect more straightforward than one had expected.

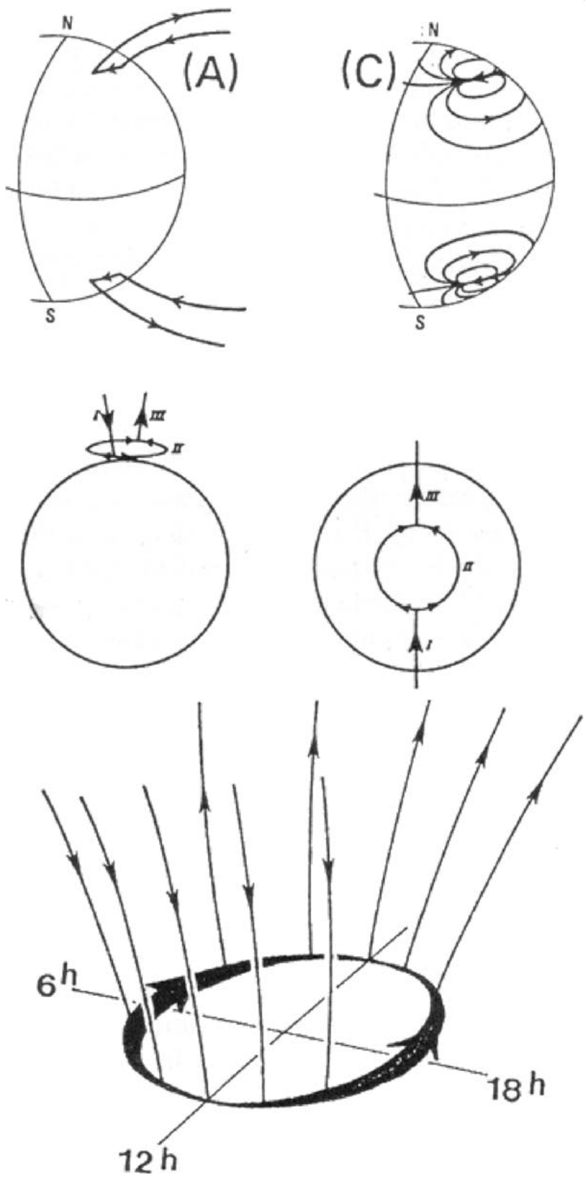


Fig. 6. The current system developed by Chapman (C) and Birkeland (A). The two middle curves illustrate what the British school used to reject Birkeland's model, while they should have used the one shown at the bottom (Fukushima, 1989).

Birkeland reached truly innovative conclusions about the physics of the aurora and disturbances in the Earth's magnetic field. *The British School* shared neither Birkeland's intuition nor his trust in laboratory simulations and felt they could explain magnetic perturbations observed on the ground as the results of a system of *equivalent currents* flowing in the upper atmosphere. Decades passed before it was shown in 1969 that it is impossible to distinguish between Birkeland's and the equivalent-current systems based on ground magnetic records alone. Field-aligned currents can only be detected with magnetometers on spacecraft flying above ionospheric current layers. Scientists are human beings who may feel that tribal loyalties blind them to truths expressed in unfamiliar words.

6. Field-aligned currents in the space age

Absolute poof for the existence of field-aligned currents could only come from satellite measurements taken above the ionosphere. In crossing field-aligned currents, magnetometers on satellites routinely detect characteristic magnetic disturbances. Unfortunately, the present technique is limited by the fact that it takes multiple spacecrafts to measure three-dimensional current fully. From the three-axis vector magnetometer on the TRIAD satellite a large-scale system of field-aligned currents nearly co-terminal with the auroral oval was discovered.

During the space age, several papers based on mathematical models and simulations regarding associated three-dimensional currents have been published (cf., e.g. Bostrøm, 1967). In addition, Vasyliunas (1970) demonstrated from theoretical energy considerations that equivalent ionospheric currents could not be sustained without field-aligned currents.

Field-aligned currents have far-reaching significance for understanding solar–terrestrial relations.

Many observations of Birkeland currents and their association with magnetic disturbances have been reported in recent decades. Patterns of such large-scale currents deduced from satellite measurements are supported by observations of electric field and auroral particles.

Birkeland currents are critical for understanding electrical coupling between the magnetosphere and the auroral ionosphere. Global intensities can reach several million amperes. The energy they dissipate in the upper atmosphere can exceed that deposited by electrons and ions that cause intense aurora displays.

Today, many plasma physicists are convinced that many phenomena such as

1. auroral rays, auroral arcs and bands with ray structures,
2. auroral electrojets,
3. inverted-V structures in particle precipitation, and
4. flux ropes

result from streams of Birkeland currents (Egeland and Burke, 2005).

Birkeland currents are most probably involved in several other phenomena in the plasma universe. Peratt (1996) has suggested that pinched Birkeland currents are the mechanism responsible for initiating the gravitational collapse of matter in the plasma state.

7. Conclusion

Birkeland published 88 scientific papers; 32 of them appeared in *Comptes Rendus des Sciences*, the journal of the French Academy. The others were published in German, Scandinavian and English journals. He also wrote three scientific books. His main treatise *The Norwegian Aurora Polaris Expedition of 1902–1903* fills more than 800 pages in large format. The other two books are about 200 pages in length. Several scientists have ranked him among the world's leading experimental physicists (cf., e.g. Peratt, 1996; Lundin, 2002). He identified and employed many promising young students who grew to become important leaders in the Norwegian scientific community. Among these were Sem Sæland, Carl Størmer, Lars Vegard, Ole A. Krogness, Thorald Skolem, Karl and Olaf Devik. They all contributed to the development of cosmic geophysics, a new field of research started by Birkeland.

Many of Birkeland's insights about the physics of space passed unrecognized until satellites gave us the ability to survey electromagnetic environments beyond our atmosphere. He introduced basic concepts that are central to modern space physics. They include calculations of energetic-particle motions in dipolar magnetic fields, his description of geomagnetic substorms, and his postulate that electric currents flow along magnetic field lines into and out of the upper atmosphere, today called the *Birkeland currents*. Birkeland's field-aligned currents have gained almost universal acceptance.

These currents link the upper atmosphere to the distant reaches of geospace. He also discovered the global pattern of the electric currents in the polar ionosphere. Based on his own laboratory simulations Birkeland was first to suggest how charged particles from the Sun control geomagnetic disturbances and might influence such interplanetary phenomena as Saturn's rings, comet tails and zodiacal light. As space measurements accumulated in the 1970s, attitudes towards Birkeland's work on electric currents in space changed to admiration and acceptance. In retrospect, we see that Birkeland's geomagnetic and auroral research, conducted between 1894 and 1913, was decades ahead of its time.

Shortly after his death in Tokyo, colleagues assembled all of Birkeland's scientific papers for return to Norway. The ship bearing the papers was lost at sea, and with it access to Birkeland's mature thoughts on auroral phenomena.

Birkeland was nominated for a Nobel Prize four times each in chemistry and physics. The government of Norway honored him as the world's first space physicist. His portrait, along with his terrella experiment and some original drawings, appears on the 200 kroner banknote, first issued in 1994. Birkeland was the first and only Norwegian scientist to be honored by the government on a banknote. In addition, a large international Birkeland Symposium was held in 1967. In order to commemorate Birkeland's great achievements in both basic and applied research, the University of Oslo, in cooperation with the Norwegian Academy of Science and Letters, and Norsk Hydro A/S inaugurated in 1986 a lecture series called *The Kristian Birkeland Lecture*.

For a detailed biography of Birkeland's life and work, the reader is referred to the recent book by Egeland and Burke (2005).

Acknowledgements

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