## Preface

The University of Oslo has since 1987 organized a Birkeland Lecture in cooperation with the Norwegian Academy of Science and Letters and the Norwegian company Norsk Hydro ASA (from 2004: Yara International ASA). The lecture takes place to commemorate the Norwegian scientist Kristian Birkeland.

Except for 1993 – when the lecture was given in Tokyo – the lectures have been given in Norway, most of them at the Academy in Oslo. Some years seminars have been organized in connection with the lectures, e.g. in 1993 when the lecture was part of a ”Joint Japanese-Norwegian Workshop on Arctic Research”, and in 1995 when the lecture was part of a seminar on Norwegian environmental research. Also in 2001, when professor D. Southwood from ESA gave the Birkeland Lecture, a workshop on Norwegian space research with emphasis on the Cluster programme was organized at the University of Oslo.

In 2005 the Birkeland Lecture was included in a one day seminar organized as part of the celebration of Hydro’s (and Yara’s) 100 years anniversary. Apart from this anniversary, 2005 was also a special year since it was decreed as the World Year of Physics by the United Nations, and Kristian Birkeland was honored by the Norwegian Committee to represent Norwegian physics and the Norwegian physicists in this year. Hence the seminar was also a celebration of the person Kristian Birkeland, who probably is the internationally best known Norwegian physicist. The topic for the seminar was Kristian Birkeland as scientist, innovator and industry founder, and Dr. William J. Burke was invited to speak about *Kristian Birkeland´s message from the Sun – its meaning then and now*.

This cooperation with the Academy, Hydro and Yara has given the University of Oslo the opportunity to invite many outstanding scientists within the area of geophysical and space research to Oslo, areas which were important in Kristian Birkeland’s own research. The lectures have without doubt contributed to a strengthening of the Norwegian international collaboration within space research and geophysics – including research on the Northern Lights which was one of Birkeland’s main interests.

The organizing committee is very grateful to the Faculty of Mathematics and Natural Sciences at the University of Oslo, the Norwegian Academy of Sciences and Letters, Hydro and Yara for the support and good cooperation through all these year. Thanks are also due to The Norwegian Space Center which has supported the Birkeland Lectures in recent years. In particular, the committee is most thankful to Dr. Burke for his important contribution to the Birkeland Seminar in 2005.

Professor Tore Amundsen
Chairman of the of the organizing committee
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# Kristian Birkeland's Message from the Sun: Its Meaning Then and Now

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*We now see in a mirror dimly* (I Cor. 13/12)

Our discussion probes Kristian Birkeland's recognition of the physical connections between the Sun and the Earth at a time when many scientists still believed that the Earth was immersed in a vacuum. Such an exploration is not easy. To grasp the enormity of Kristian Birkeland's contributions to space science we must place ourselves inside of his world. Over the century that separates us access to space has increased the quality and quantity of our knowledge beyond Birkeland's wildest dreams. The task might be simpler if we explained Birkeland's discoveries in the scientific language of our day. By and large, I have chosen not to do so. Using today's language obscures the intellectual challenges that Birkeland and his contemporaries faced and overcame. While Birkeland lived in an era of great scientific ferment, such critical terms as 'electrons', 'plasmas' and 'ionosphere' had not yet entered the standard physics lexicon. Our challenge is to make sense of the worldviews of Birkeland and other scientists of his and subsequent generations using language they created as understanding grew. Although some of that terminology has not survived into the present day, their abiding legacy consists of the radically new perspectives on the world they passed on to us.

On the nights of September 9 and 10, 1898, dazzling auroral displays danced across the skies of northern and central Europe, bringing with them strong magnetic disturbances and widespread telegraphic disruptions. These events piqued the interest of Kristian Birkeland (1867-1917) then a young professor of physics at the University of Kristiania. His ongoing research on cathode rays, illustrated in Figure 1, produced distributions of visible light around magnetic poles that were uncannily similar to aurora. Two years earlier Birkeland (1896) was the first to suggest that auroral light might be caused by cathode rays from the Sun hitting the upper atmosphere, as shown schematically in Figure 2. With this possibility in mind, Birkeland immediately asked “Was anything unusual happening on the Sun?” Indeed there was! Solar observers had seen large sunspots appear at the eastern limb of the Sun on September 2, cross the central meridian on September 8, then disappear behind the western limb on September 14.

Figure 1: Photograph of Birkeland’s most successful artificial aurora produced with cathode rays inside a device that he called an auroral jar (Birkeland, 1896). The tube was placed in a large magnet. The cathode was located in a twice-bent glass tube that merged into the container. The anode was mounted in a small sphere connected by a narrow tube to the large sphere.

On September 16, 1898 Kristian Birkeland published a popular article on these recent happenings in *Verdens Gang* that he called *Sunspots and Northern Light: A Message from the Sun* (Birkeland, 1898).

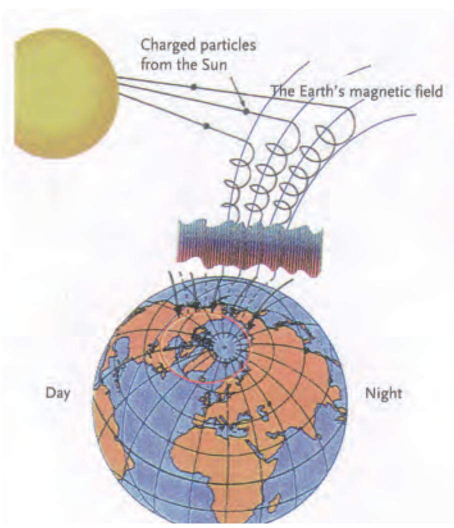



Figure 2: Illustration of Birkeland’s auroral theory. Charged particles from the Sun are guided by the magnetic field toward the Earth’s polar atmosphere. Hot auroral particles collide with atoms and molecules in the atmosphere. Energy is released in each collision producing excited atoms and molecules, which in turn yield the aurora.

We can consider Birkeland’s *Verdens Gang* article from several perspectives. One concerns a causal connection between phenomena physically separated by almost 100 million miles. Indeed, given its practical importance to modern society, this aspect of Birkeland’s article is the main focus of our present discussion. Second, in the course of helping Professor Alv Egeland to write a scientific biography of Kristian Birkeland (Egeland and Burke, 2005), I was intrigued by the subtitle "*A Message from the Sun*." Why did Birkeland choose this metaphor?

Messages and messengers have deep significance in western civilization. Luke's gospel begins with the appearances of a messenger (ανγελοσ) named Gabriel in Jerusalem and in a remote village of Galilee. The annunciation story ends with Mary pondering the message given to her. In the midst of the heliocentric controversies of the early 17$^{th}$ century Galileo (1564-1642) described his astronomical discoveries in a book he called *Sidereus Nuncius* (*The Stellar Messenger*). Modern physics grew out of deep and often painful reflections on Galileo's message from the heavens.

Galileo's personal travails began when the philosophy faculty at the University of Pisa denounced him to the Roman Inquisition for denying that Joshua could command the Sun to stand still (*Joshua*, 10, 12-13). Theological camouflage barely hid the real reason for their attack. Galileo's new astronomy undermined the Aristotelian worldview in which the Pisa philosophy faculty held strong vested interests. Correspondence between Galileo and Cardinal Robert Bellarmine (1542-1621), then head of the Roman Inquisition, still makes interesting reading. Bellarmine agreed that Galileo's heliocentric model gave a clearer and simpler description of planetary motion. However, Bellarmine argued, heliocentrism was not an entirely new concept. Greek astronomers had considered and eventually rejected the heliocentric hypothesis because they could not detect parallax shifts in the locations of stars over the course of a year. Until the parallax issue was resolved, Bellarmine felt that Galileo should confine his rhetoric to defending the heliocentric hypothesis. In fact, it would take another two centuries before telescope technology had sufficiently advanced for Bessel to measure the parallax of nearby stars.

Two relevant lessons may be drawn: First, in the context of physics, "messages" are hypotheses based on intuitive grasps of the larger significance of new information. The implications of the intuitions/hypotheses must then be pondered and tested. Second, the technical means needed for testing may not be available at the time that a hypothesis is proposed, or even for a long time thereafter. Both lessons are of value to us as we reflect on the historical evolution of understanding Kristian Birkeland's *Message from the Sun*.

In the *Verdens Gang* article Birkeland explicitly recognizes that the Sun's message is not simple. In favor of a connection is the fact that many large geomagnetic disturbances with auroral displays occur in conjunction with identifiable activity on the surface of the Sun. The British astronomer Richard Carrington (1826-1875) demonstrated that the great magnetic storm of September 2, 1859, occurred a day after a visible-light solar flare (Carrington, 1859). Also the occurrence rate for magnetic/auroral disturbances follows the sunspot cycle (Sabine, 1852). On the other hand, Birkeland conceded that some auroral disturbances occur without solar activity, and sunspots can move across the surface of the Sun without producing significant auroral activity. His intuitive grasp of a physical connection between the Sun and aurorae required further testing. To this end Birkeland describes the benefits of two new auroral observatories under construction in Finnmark, northernmost province of Norway.

Stepping back a few years to the academic year 1892-1893, we find the young Kristian Birkeland a scientific apprentice (a postdoc in today's parlance) to Henri Poincaré (1854-1912), a giant of contemporary mathematics and physics. Poincaré regarded intuition and analysis as the two marks of scientific greatness. Without intuition, analysis reduces to logical manipulation. The late medieval Aristotelianism with which Galileo contended exemplifies this quagmire. On the other hand, intuition without analysis produces subjective, free-floating ideas whose validity is unassessed. For the remainder of his life Poincaré was Birkeland's steadfast friend and scientific champion. Doubtless, Poincaré saw exactly these two characteristics in young Birkeland.

Let us now examine Birkeland's struggles to interpret and understand the message from the Sun. This presentation is divided into three parts in the fashion of a Hegelian triad: Birkeland's thesis, negative reactions to it, and our present synthetic understanding of the *Message from the Sun*.

## *Message from the Sun*: Birkeland's Understanding

Kristian Birkeland did not just wander out of his laboratory one evening, see an auroral display, check for sunspots then dash off an article for *Verdens Gang*. His study of electrical discharges, especially the interactions of cathode rays with magnetic dipoles had already prepared him to think about an old problem in a new way. At the beginning of the *Metaphysics* Aristotle (384-322 B.C.E.) remarked that wisdom begins when a person perceives something that causes him to say, “I wonder.” Well before the evening of September 10, 1898, Kristian Birkeland had already wondered if auroral displays were electric discharges that originate on the Sun. This well-publicized magnetic storm provided an opportunity to share his wondering with an audience that extended beyond his circle of academic colleagues. He was convinced that the near simultaneous activity on the Sun and on Earth was not an accident. Rather, it was telling us something important about Sun-Earth connections not previously thought possible.

Understanding the message required two important steps. First, Birkeland had to collect as much physical information as possible about auroral lights and geomagnetic disturbances. Second, he had to identify physical processes that allowed matter and energy to travel across almost one hundred million miles.

In the late summer of 1897, a year before the *Verdens Gang* article, Birkeland conducted a reconnoitering visit to Finnmark, the northernmost province of Norway. To gather facts about the aurora he then conducted two extended scientific expeditions. During the first, Birkeland and a few enthusiastic students spent the winter of 1899-1900 at a newly constructed auroral observatory perched on the top of the 900-meter Haldde Mountain, the highest outcrop of rock near Kåfjord, the largest town in Finnmark (Birkeland, 1901). An auxiliary station established on Mount Talvik a few kilometers away allowed simultaneous observations and estimates of auroral heights by triangulation. Some then believed that the aurorae reached upwards from mountaintops. If this were so, from his vantage at the Haldde station Birkeland would be able to look down on auroral lights.

Figure 3: Aurora over the Haldde station. This is probably the first photograph of an aurora.

The 1899-1900 expedition mixed triumph and tragedy. First, Birkeland clearly established that auroral lights come from heights well above the mountains. Figure 3 displays the first photograph of the aurora from the perspective of Mount Talvik looking toward Haldde. Second, from magnetometer measurements Birkeland correctly inferred the first global map of the auroral current system (Figure 4) characterized by a two-cell pattern. Birkeland would fill the gap at polar cap latitudes during the second expedition. Figure 5 shows the cover plate of Birkeland's book, written in French, on the expedition's results. The bold display of the Norwegian flag while Norway was still part of the Swedish kingdom, attests to Birkeland's ardent patriotism. Elisar Boye, a student of classical literature who had volunteered for the expedition, sketched the Haldde observatory with Mount Talvik in the background. Near the end of the expedition Boye and Richard Lange, a local worker, died in an avalanche. Birkeland, deeply saddened by the loss, later wrote to his parents, “The image of Boye will always stay with me.” Through managerial inexperience the 1899-1900 expedition introduced another scientific first, a large cost overrun. The final tally of 38,297 kroner exceeded Birkeland’s 12,000 kroner proposal by more than a factor of 3!

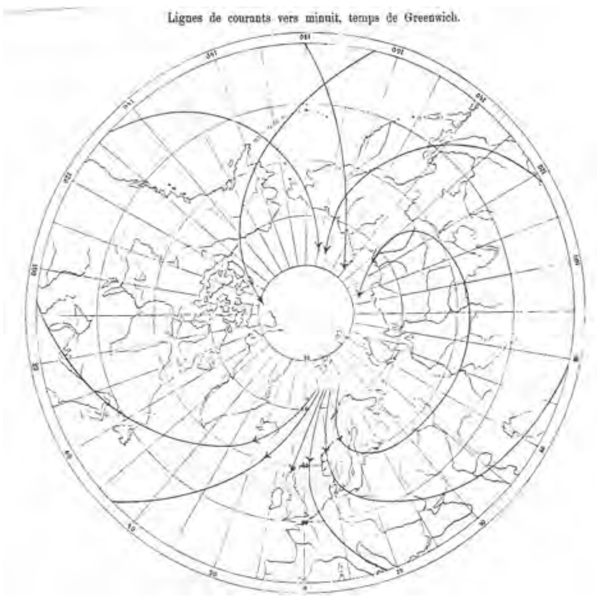



Figure 4: Current patterns viewed from above the North Pole. Birkeland called the drawn curves “lines of currents at midnight, Greenwich time.” Global ionospheric currents are represented in a coordinate system oriented with respect to the Sun. Earth rotates under the current pattern, indicated by the curved lines, in 24 hours (Birkeland, 1901).


Figure 5: Title page of Birkeland’s second book, printed in 1901, shows a picture of the Haldde and Talvik Observatories drawn by Elisar Boye.

The second and more important Norwegian auroral expedition took place under Kristian Birkeland's leadership during the winter of 1902-1903. Simultaneous measurements of auroral emissions and magnetic perturbations were made at four identical but widely spaced stations (Figure 6). Three of them were located in the normal auroral zone, at Matotchkin Schar on Novaja Zemlya, near Kåfjord, Norway, and at Dyrafjord, Iceland. The fourth was located poleward of the auroral oval near Axeløen, Spitzbergen not far from the modern Norwegian Observatories at Ny Ålesund and Longyearbyn.

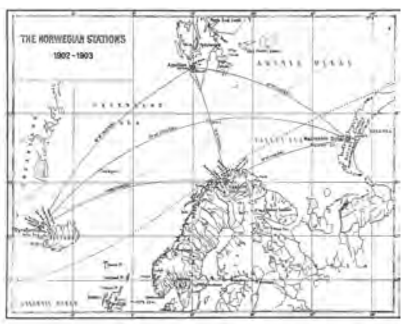
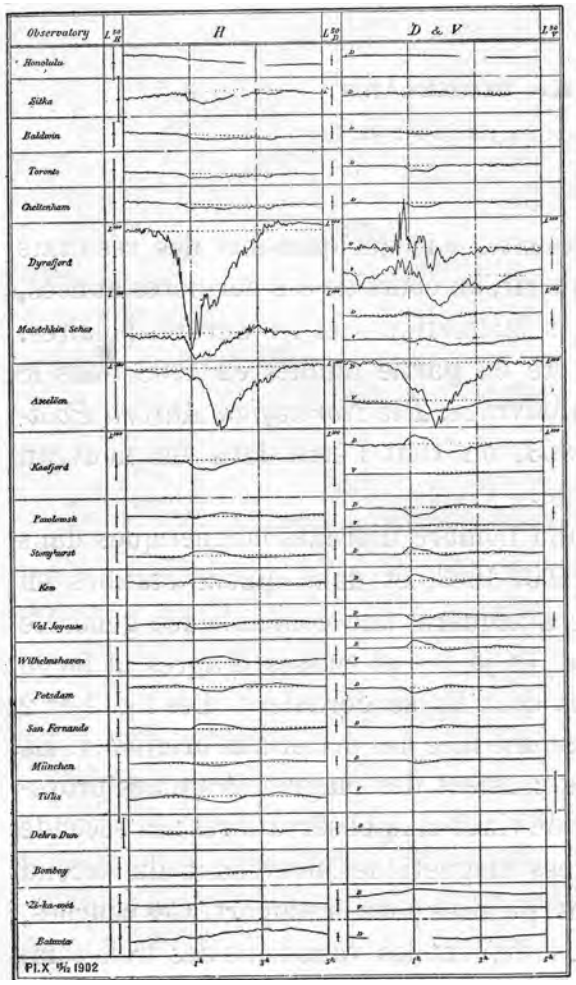



Figure 6: Map showing locations of the four stations established in 1902 to chart variations in the Earth's magnetic field. Stations were about 1000 km apart.

Large geomagnetic campaigns had been mounted previously, but the expedition of 1902-1903 was unique. Birkeland purposely chose to distribute four identical magnetometers that allowed him to discover the systematics of magnetic perturbations at both auroral and polar cap latitudes. In the light of Ampere's law and Gauss' magnetic potential theory Birkeland knew that currents flowing in the upper atmosphere caused the observed magnetic perturbations. He modeled currents as if they were flowing in wires and made reasonable (correct) estimates about their altitudes. From the relative strengths of magnetic perturbations he estimated the strength and orientation of the global current system. Figure 7 presents stacked magnetic-field plots from which Birkeland deduced current patterns. The astounding answer was that several millions of Amperes flowed in the upper atmosphere during disturbed periods. What energy source was strong enough to sustain such large current? His answer: the Sun. How could electromagnetic energy from the Sun couple to the upper atmosphere? His answer: through electric currents that flow from deep space, along magnetic field lines into the polar atmosphere then return along other magnetic field lines to space. A sketch of Birkeland's perception of the necessary electrical circuit appears in Figure 8. Today we would say the currents flow in the ionosphere. However, when Birkeland was writing his report, *The Norwegian Auroral Polar Expedition of 1902-1903* (NAPE), little was known about the electrified layer in the atmosphere above 100 km. The physical properties of the ionosphere would remain unexplored for more than a decade.



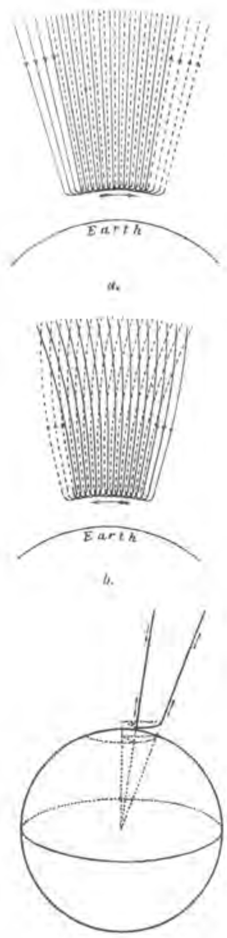




Figure 7 (left): Typical magnetic recordings from 22 stations. More than 30 such diagrams are included in NAPE. The deepest disturbances were observed at Birkeland's four stations.

Figure 8 (right): Original field-aligned current systems suggested by Birkeland in 1908. This is Figure 50 in Vol. 1, NAPE; p. 105 *On the Cause of Magnetic Storms and the Origin of Terrestrial Magnetism.*

In his analysis of magnetic disturbances Birkeland described three typologies found at: (1) auroral latitudes near local midnight, (2) all latitudes and local times, and (3) equatorial latitudes near local noon. While Birkeland's original nomenclature was lost in later years, his accurate descriptions of the phenomenologies have guided the development of ionosphere-magnetosphere coupling theory to this day. His genius was to express the problem in terms of a simple electric circuit. How much current flows in the polar cap and at auroral latitudes? As we see below, the subtlety of nature would hide key features of the circuit until properly equipped spacecraft flew above the auroral currents whose effects Birkeland could observe on the ground.

Birkeland's laboratory experiments described in NAPE took two basic forms. He used magnetized terrellas as either anodes (positive potential) or cathodes (negative potential) to simulate different aspects of the Sun-Earth circuit. From a distance he would fire cathode rays at the terrella and photograph the distribution of visible light they produced about the magnetic poles. With Carl Størmer (1874-1957) he calculated and experimentally checked the trajectories of cathode rays in the terella's magnetic field. Figure 9 shows an example of simulated auroral lights produced near Birkeland's magnetized terrella when bombarded by cathode rays as well as the Størmer trajectories of cathode-ray particles approaching the terrella. Neither Birkeland nor Størmer had any way to verify whether the energies of his simulated auroral particles matched those found in nature. However, nothing in his simulations precluded a solar source for the aurora.

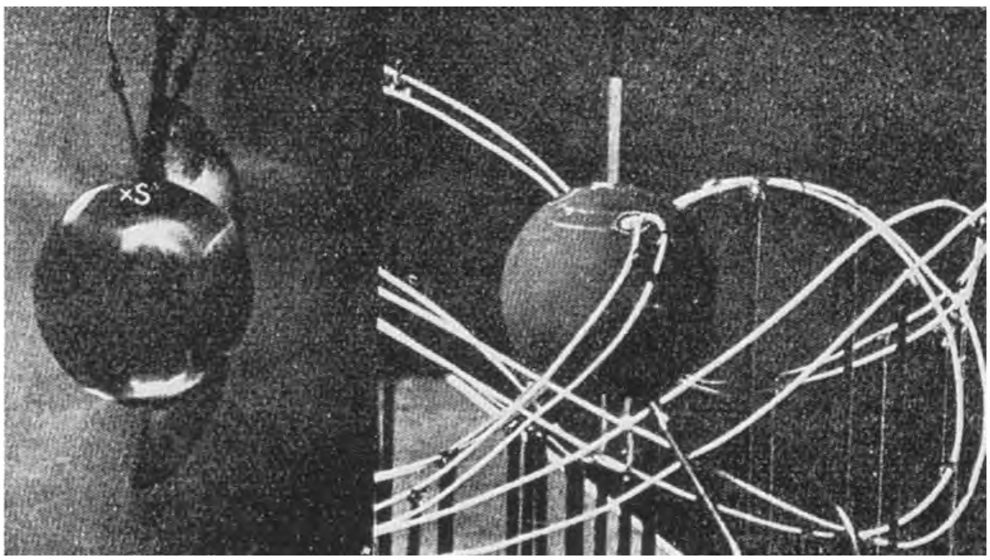



Figure 9: Birkeland's terrella with auroral zones (left) and trajectories Størmer calculated for charged particles in a dipole magnetic field (right). Agreement between the experiments and calculations is excellent. Figure is from a 1907 paper describing experiments in a cylindrical 12 litre chamber (NAPE, p. 159).

When Birkeland reversed the terella's electric polarity he turned it into a source of electron beams rather than the target. Emitted electrons tended to escape from magnetic-polar regions and then bend toward the equator as they propagated away from the simulated Sun. He noted that surface sputtering caused pitting on the "solar" surface that resembled sunspots. In turn, pitted regions became sources of intense electron emissions. Birkeland was convinced that his simulations had uncovered the causal connection between sunspots and aurorae. His explanatory model required that convection beneath the photosphere left the solar surface negatively charged. Electrostatic force caused sputtering which allowed intense cathode rays to escape into space. Some of these beams would intercept the Earth and cause visible light. To the objection that the cathode rays would be torn apart by Coulomb repulsion long before they reached Earth (e.g. Schuster, 1911), Birkeland responded that cathode rays escaping the Sun drag positive ions along with them. Thus, material found between the Sun and the Earth should be an electrically neutral ionized gas, with roughly the same number of positive as negative charged particles.

Over the 15 years between the *Verdens Gang* article and the publication of NAPE, Vol. 2, Birkeland's grasp of the message from the Sun evolved substantially. His terrella simulations and analyses of magnetometer measurements led him to conclude:

(1) Electrostatic forces on the solar surface cause negatively and positively charged particles to stream away from the Sun continuously. This was the first scientific prediction of what we now call the solar wind.

(2) Both species are drawn into the Earth's magnetic field and impact the upper atmosphere. However, in Birkeland's view, negatively charged particles stimulate visible auroral emissions, a claim later disputed by his student Lars Vegard (1880-1963) but essentially accepted by his chief adversary Sydney Chapman (1888-1970).

(3) Intense electrostatic sputtering led to the formation of dark regions on the surface of the terrella, analogous to sunspots. The most intense cathode rays flowed from these surface blemishes. This characteristic seemed to explain why bright auroral emissions and geomagnetic disturbances often occurred when large sunspots faced the Earth.

(4) Electric currents that connect ionized gas from the Sun with the Earth's polar atmosphere intensify during disturbed periods. In part these currents flow along magnetic field lines and across the upper atmosphere in patterns revealed by the directions and strengths of magnetic perturbations measured on the ground.

Because of his commitment to the commercial development of nitrogen-based fertilizers Birkeland found little time to analyze data collected during the 1902-1903 campaign until 1906. The first two volumes of NAPE, published in 1908 and 1913, contain little explicit, new information about the auroral lights. He chose to defer this discussion to his planned Volume 3 that, unfortunately, was never completed. Shortly after his death in June 1917 Birkeland's notes and preliminary manuscript were shipped to Norway from Japan aboard the ship *Peking* that was lost off the coast of Korea. Although the existing two volumes of NAPE have few auroral insights, Birkeland had not lost interest in the message from the Sun. Rather his emphases shifted to electrical currents responsible for geomagnetic disturbances and to laboratory simulations of geophysical phenomena with terrellas, because they provided new tools for characterizing Sun-Earth connections. My research experience attests to the almost irresistible draw of new data and fresh perceptions when reporting scientific results.

Of course not everyone believed either Birkeland or the message. It is widely accepted that in 1892 Lord Kelvin had dismissed a solar-terrestrial relationship as coincidental. After 1918 Professor Sydney Chapman modeled observed magnetic disturbances in ways that would render Birkeland's field-aligned currents superfluous.

## *Message from the Sun:* Rejected

For his contributions to the emerging field of thermodynamics Sir William Thomson (1824-1907), also known as Lord Kelvin, was considered a titan of $19^{th}$ century physics. One particular segment of his presidential address to the Royal Society (Kelvin, 1892) is often quoted,

> It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is unreal, and that the seeming agreement between the periods has been mere coincidence.

Over the past three decades I have seen this quotation in books and articles on the solar wind, with the authors usually claiming that Kelvin thereby set back understanding of Sun-Earth relations by 50 years. It would appear that Kelvin's comments had chilling consequences. However, the phrase "we may also be forced to conclude" suggests that his opinion was expressed within the context of a larger discussion. What might that context have been?

Prior to reading Kelvin's address to the Royal Society, I had assumed that in 1892 little was known about the Sun beyond the characteristics of the photosphere whose temperature is about $5000^{o}$ K. In the energy units now commonly used this corresponds to approximately one half an electron-Volt. For a particle to reach Earth it must overcome the binding force of gravity. To escape from the photosphere into space a particle must have a velocity

$v_{esc} = \sqrt{\frac{2GM_s}{R_s}}$ ≈ 620 km/s. For protons this corresponds to a kinetic energy of ~2000 electron-Volts or a temperature of two million degrees.

However, my assumption was not accurate. During a solar eclipse in December 1870 the Jesuit astronomer Angelo Secchi (1818-1878) witnessed coronal prominences moving away from the Sun at near escape velocities. In 1892, the year of Kelvin's address to the Royal Society, Gerald Francis Fitzgerald (1851-1901) asked "Is it possible then that matter starting from the Sun with the explosive velocities we know possible there, and subject to an acceleration of several times the solar gravitation, could reach the Earth in a couple of days?"

Kelvin's remarks read in this context give a very different impression. They contain no mention of corpuscular radiation from the Sun! Rather, he was addressing a current hypothesis that the Sun had a very strong magnetic field whose fluctuations induced currents that drove magnetic storms on Earth. To test this concept he analyzed the energetics on the Sun required to explain a well-documented magnetic storm in 1885. The required power in magnetic fluctuations would have to be ~400 times greater than that emitted as visible light by the Sun. What Kelvin actually rejected was a wrong concept of solar-geomagnetic coupling. In fact he then went on to encourage scientists to continue to pursue understanding of Sun-Earth connections. It may well be that Kelvin's contemporaries and later scientists read much more than he intended into his remarks.

Kelvin spoke six years before Birkeland wrote his article for *Verdens Gang* and appears to have had no direct effect on his research. However, Birkeland's investigations of electrostatic emissions of cathode rays from terrellas, as applied to the Sun, may well be viewed as a specific mechanism for overcoming the binding effects of gravity. At a time when most properties of the solar corona were largely unknown, gravitational-escape issues had to be regarded as substantive. Birkeland was too careful a scientist to regard the case for an ionized gas streaming away from the Sun as empirically proven. Indeed his last four years were spent in Egypt trying to demonstrate the presence of matter in interplanetary space from modulations of zodiacal light during magnetically disturbed periods. Zodiacal light is sunlight that scatters off dust particles orbiting near the ecliptic plane. Birkeland felt that if his surmise were correct then zodiacal light ought to intensify and develop new spectral lines as dust particles were bombarded by cathode rays from the Sun. There was still much to learn about the solar corona before we could model and understand how an ionized gas flows away from it.

Although educated as a mathematician, Sydney Chapman turned his talents and attention to a wide range of physics problems related to aeronomy, astronomy, crystallography, geomagnetism, and kinetic theory of gases (Sugiura, 1984). By any standard Chapman was a prolific writer of scientific articles and books over a long and illustrious career. His earliest papers on geomagnetism concerned the influences of atmospheric tidal motions, induced by the Moon and Sun, on the diurnal variability of the Earth's magnetic field (Chapman, 1913). About a year after Birkeland's death, Chapman

(1918) began to model geomagnetic storms. He first collected records acquired at stations around the globe. Fukushima (1994a) suggested, "Perhaps Chapman was inspired by a monumental work of Moos (1910), who studied the average characteristics of 113 magnetic storms having sudden commencements during 1872-1904." Chapman then meticulously subtracted quiet time diurnal variations of fields at each station to show that all storms begin with sudden increases in the horizontal (northward) component of the field almost simultaneously around the world. The horizontal component then decreased to a minimum for up to 24 hours and recovered slowly over several days. Through his empirical studies Chapman bequeathed to the space sciences the general morphology that guides our analyses of storms to this day. Although Chapman's nomenclature differed from Birkeland's description of combined equatorial and polar-elementary disturbances, the morphology was essentially the same. Because of their different methodologies, Chapman had a larger database from which he could draw statistical inferences about storm development.

The rift between the worldviews of Birkeland and Chapman (Scandinavian and British schools) formed on the level of interpretation not morphology (Fukushima, 1994b; Akasofu, 2003). Birkeland inferred that the millions of Amperes of current flowing in the upper atmosphere during disturbed times required a solar source mediated by field-aligned currents. Under the implicit influence of Kelvin's negative assessment of a solar source for magnetic storms, Chapman looked for a different way to explain the existence of storm-time currents (Dessler, 1984). At the 1967 *Birkeland Symposium on Aurora and Magnetic Storms* Chapman confessed that it was his "disbelief of Birkeland's theory of electron streams" that caused him "unwisely" to disregard much of his work.

However, to the degree that Chapman's recollection is accurate, it reflects the objection of Schuster (1911) and Lindemann (1919) rather than Kelvin (1892). For Chapman the only plausible, alternate source for generating the required millions of Amperes seemed to be natural motions of the upper atmosphere. His previous studies of lunar effects on diurnal magnetic variations made such a conjecture seem reasonable. For Chapman (1918) the unique difference between magnetically quiet and disturbed times was the presence of energetic positive and negative charges impacting the upper atmosphere. He agreed with Birkeland that the negative charges were primarily responsible for auroral lights and the ionization of the upper atmosphere stopping layer. He also argued that the momentum of down-coming negative charges of direct solar origin initially compressed the Earth's magnetic field giving rise to the sudden storm commencement signature observed throughout the world. However, over time negative space charge would accumulate in the upper atmosphere creating strong vertical electric fields that push the ionized gas and neutrals upward to relieve the initial compression. Since the atmospheric conductance would be elevated by the impacting charged particles the combined atmospheric motions and the electric fields would drive the large currents responsible for magnetic signatures seen on the ground. Chapman seemed unaware of the close convergence of his thoughts about the auroral source with those of Birkeland. We note that neither Chapman nor his contemporaries conceived of a ring current encircling the globe several Earth radii above the surface that drives the characteristic perturbations of magnetic storms, a concept that lay four decades in the future (Stern, 2005).

A year later Lindemann (1919) criticized Chapman's model and found it wanting. Specifically, he claimed that Chapman regarded alpha particles as the source of storm-time currents, then showed that the required level of solar radioactivity needed to sustain these currents was unreasonably large. Like Schuster (1911) he also argued that charged particle beams of a single species would be destroyed by Coulomb repulsion. He then proposed that equal numbers of positively and negatively charged particles must exit the Sun and impact the Earth's magnetic field, a suggestion similar to Birkeland's ideas. After a nine-year hiatus Chapman (1927) returned to the subject of magnetic storms. In deference to the Schuster/Lindemann critique, he rejected his own earlier speculation about solar particles and said that he regarded Birkeland's model as suffering from the same fatal flaw. At this juncture Chapman seems to have missed Lindemann's positive suggestion about how a corpuscular solar-terrestrial coupling might be effected.

While Chapman's system of equivalent currents seems to explain storm-time morphology it left two substantive questions unanswered. First, if the energetic particles present during storms do not come from the Sun, where do they originate? Second, why does the reservoir for the charged particles discharge them into the upper atmosphere so efficiently during magnetic storms? By the mid 1930s Chapman and Ferraro had developed a new theory of magnetic storms that allowed bursts of plasma to escape from the Sun then impact and compress the Earth's magnetic field (Chapman and Ferraro, 1931). This acceptance of a solar source explained the sudden commencements of storms. They still lacked the understanding needed to explain the main and recovery phases of storms. However, this concession set the stage for the revival of the energetic particle portion of Birkeland's message from the Sun.

In Birkeland's view the message from the Sun implicitly included an electrical connection to currents flowing in the upper atmosphere. Vestine and Chapman (1938) challenged Birkeland's field-aligned current-driven stormtime circuit head on and claimed the model was fatally flawed. They compared magnetic perturbations on the ground as predicted by Birkeland's field-aligned currents with their model of equivalent currents. Their calculations led them to conclude: "In the case of Birkeland's model a good fit with observations near the auroral zone implies a poor fit with observations near the center of the zones and *vice versa*." To Professor Naoshi Fukushima this conclusion seemed difficult to understand. From the viewpoint of ground magnetometers his analysis showed that the Chapman-Vestine and Birkeland current systems were equivalent (Fukushima, 1969). It would take another twenty years before Fukushima (1989) discovered an unintentional misrepresentation of Birkeland's current in Vestine and Chapman (1938). Here we find that testing the message/hypothesis involves fallible human beings who can genuinely misunderstand each other as they struggle with complex natural phenomena.

## *Message from the Sun*: Contemporary Understanding

As Birkeland's understanding of the message evolved, he focused on two related issues, corpuscular radiation from the Sun and field-aligned currents coupling the upper atmosphere to distant space. In the decades after his death the British school rejected both aspects of this understanding, while a cadre of Birkeland supporters continued to press for his case (Egeland, 1984; Dessler, 1984). On both experimental and theoretical levels a consensus about the existence of corpuscular radiation from the Sun was reached well before the field-aligned currents debate was resolved. The following brief sketches of both developments illustrate the evolution in scientific understanding and the essential role of advanced technologies.

### (a) Birkeland's Solar Particle Hypothesis

The case favoring solar corpuscular radiation as a source of magnetic disturbances grew steadily. As seen above, during the very year of Kelvin's seemingly pessimistic evaluation of a solar source for magnetic storms Fitzgerald (1892) suggested that explosive sources on the Sun could accelerate particles to very high speeds. Escape from the gravitational pull of the Sun was indeed perceived as a critical issue in the 1890s. Birkeland proposed electrostatic propulsion as a possible mechanism for that escape.

At the Greenwich Observatory Maunder (1905) was building the statistical database needed to determine relationships between sunspots and magnetic storms. From this database Greaves and Newton (1929) would demonstrate that magnetic storms come in two distinct forms. Small storms tend to repeat from one solar rotation to the next irrespective of sunspot activity. Large storms are non-repeating and coincide with the presence of large spots on the solar disk. By the time Chapman and Ferraro (1931) published their model of sudden storm commencements based on solar energetic particles compressing the Earth's magnetic field, the theoretical battle over the existence of a corpuscular connection between the Sun and the Earth was essentially won. Several years before satellites ventured into the solar wind Biermann (1951) found optical evidence suggesting that comets frequently have two tails. One consists of neutral gas and dust and aligns with the comet's trajectory. The other is directed radially away from the Sun and consists of ions convecting radially outward along with invisible streaming matter. Experimental confirmation of corpuscular radiation from the Sun moved scientific concern to the challenge of identifying its source(s).

By the mid 1930s spectrographic information indicated that the solar corona had a temperature close to a million degrees (Grotrian, 1934). With this information Chapman (1957) developed a model of the Sun's upper atmosphere in which gravity and atmospheric pressure exactly balanced and estimated the density of the solar atmosphere in the vicinity of Earth. Parker (1963) took the opposite path assuming that in the corona the thermal pressure and gravity were not in equilibrium. This implied that ions and electrons must flow away from the Sun in all directions at supersonic speeds. Satellite measurements largely confirmed Parker's dynamic model and rejected Chapman's static one. Could Parker have reached his conclusions about the solar wind before aerodynamics scientists studied fluid transitions to supersonic speeds in the 1940s and 1950s?

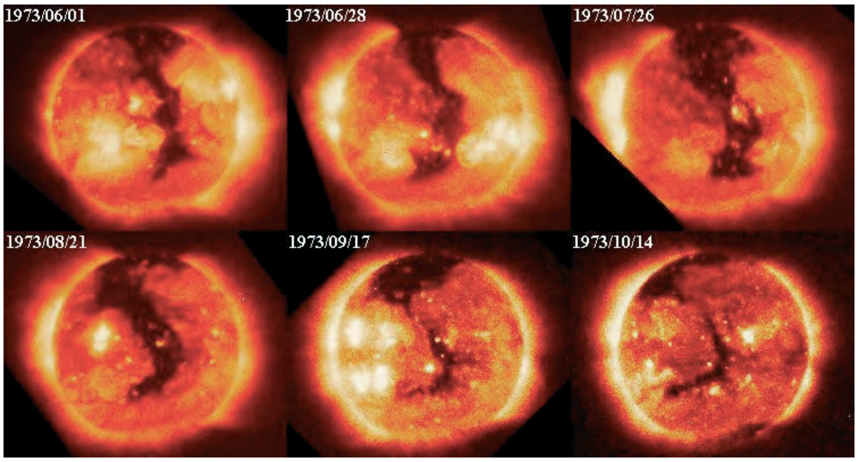



Figure 10a: Development of a solar coronal hole observed at X-ray wavelengths by Skylab in 1973.

However, satellite observations soon showed that plasma flow away from the Sun is not the same in all directions. In 1973 the x-ray imager on Skylab revealed that the Sun develops large patches of suppressed emissions called

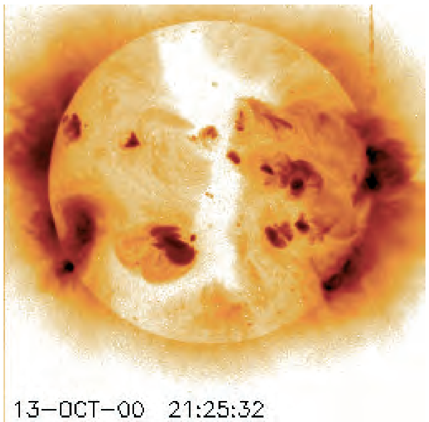



Figure 10b: A solar coronal hole observed by the Japanese satellite Yohkoh (Sunbeam) in October 2000.

coronal holes (Figure 10a,b) which are most evident during solar minimum. Within coronal holes the Sun's magnetic field is very weak and thus allows solar wind plasma to move outward in fast-flowing streams. Generally coronal holes and fast plasma streams last for several solar rotations and give rise to the repeating magnetic storms.

During active solar periods billions of tons of matter, called coronal mass ejections (CMEs), sporadically explode from the Sun (Figures 11 and 12). They appear to grow out of intense magnetic flux that emerges from the interior of the Sun through large sunspots, accelerates into the corona then breaks off as shown schematically in Figure 13. If the CME source is pointing toward Earth at the time of the explosion the ejected, fast-moving plasma will drive very large magnetic storms.

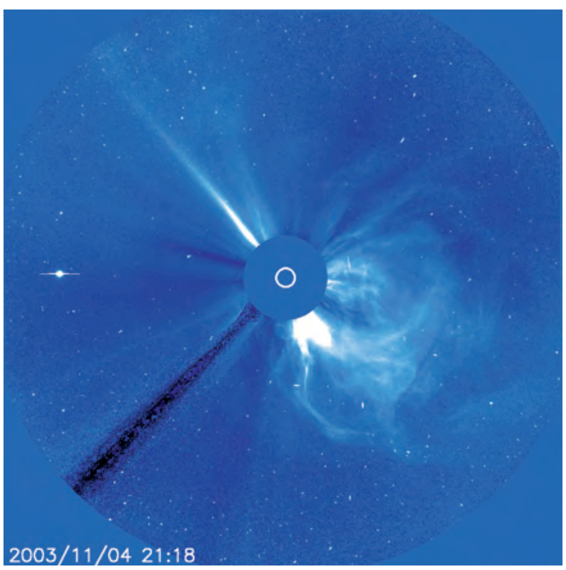



Figure 11: LASCO coronagraph images of CMEs erupting from the surface of the Sun on 04 November 2003 when the largest X-ray flare ever recorded was observed.

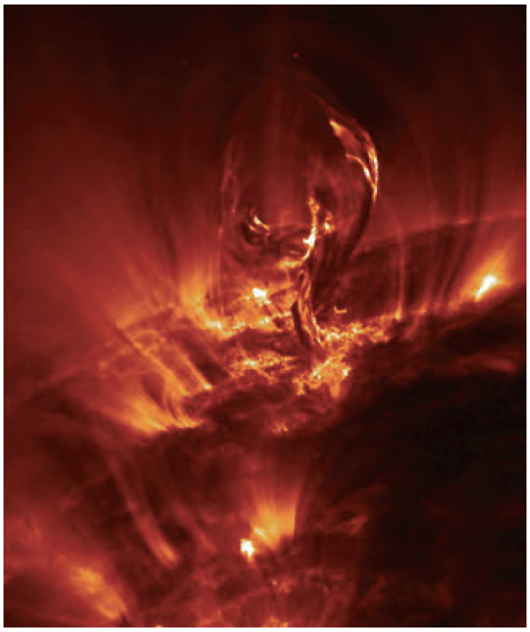


Figure 12: Image of a CME erupting from the Sun recorded by the TRACE satellite.

Birkeland's notion of electrostatic acceleration as the way nature accelerates particles away from the Sun was erroneous. Violent electromagnetic processes beyond his ken were the real culprits. Extrapolating from his terrella experiments and his knowledge of large magnetic storms Birkeland suggested that intense beams of energetic particles from sunspots might cause auroral lights. However, many aspects of this complex puzzle were hidden from his view and required the development of advanced technologies for viewing the Sun from above our atmosphere which absorbs critical information at ultraviolet and X-ray wavelengths. Others demanded satellite-based exploration of the energetic particle populations in the outer reaches of the Earth's magnetic field.

Recall that the primary title of Birkeland's *Verdens Gang* article was "Sunspots and Aurora." His laboratory experiments suggested that energetic electrons from the Sun are the immediate causes of auroral emissions. The trajectories of incoming cathode rays indeed seemed to follow closely those mathematically predicted by Størmer. However, it turned out that solar wind electrons have much lower energies than those used in the Størmer-Birkeland calculations. The low-energy electrons can only reach the auroral ionosphere directly from the solar wind along magnetic field lines connected to the dayside cusps. The cusps are weak points in the Earth's magnetic shield that are found near local noon. Typically they map to ~78$^{o}$ magnetic latitude in the dayside ionosphere. The world's best locations for observing dayside aurorae

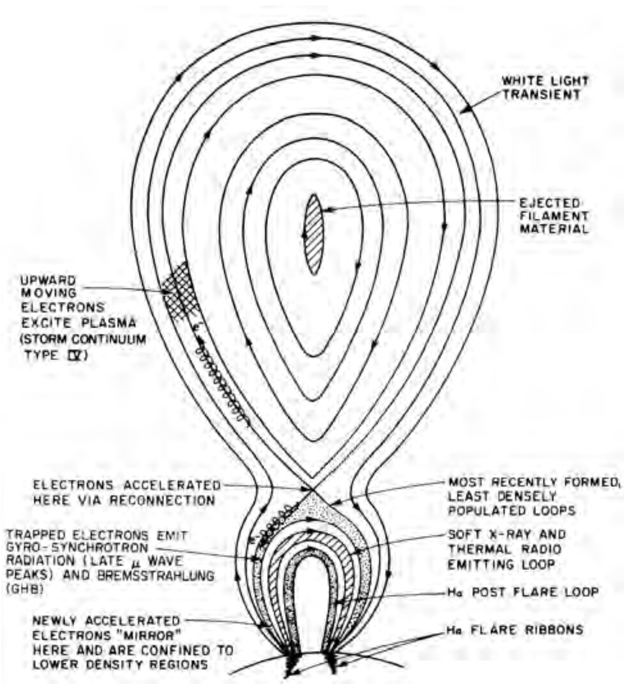



Figure 12: Schematic of a coronal mass ejection (CME).

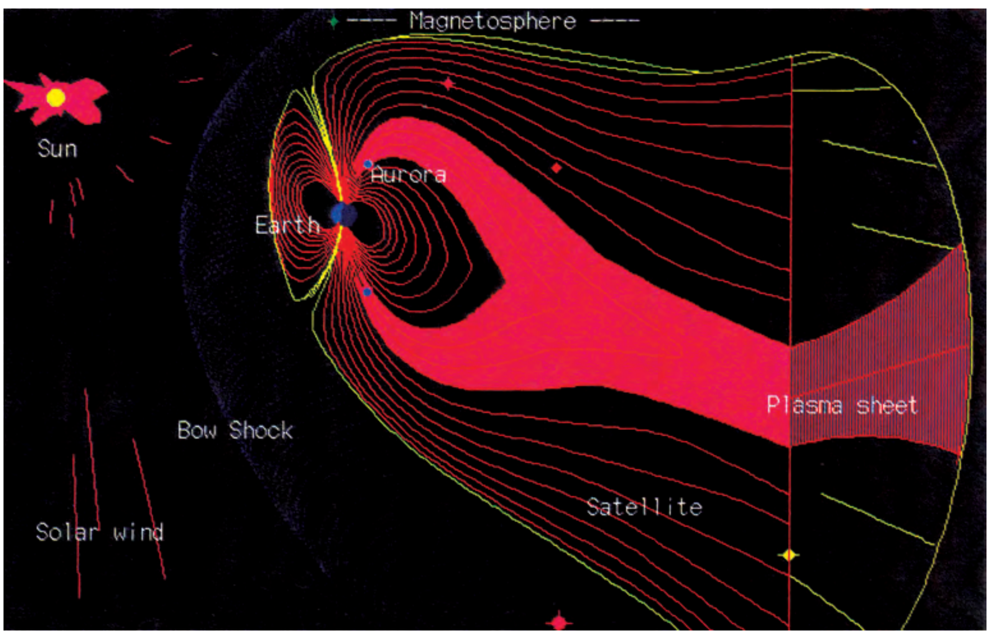



Figure 14: A sketch of the configuration of the Earth's magnetosphere. The center blue point is the Earth; red lines illustrate the Earth's magnetic field. The bow shock in front of the Earth and the plasma sheet are also shown. The interplanetary magnetic field has a modulating effect within the magnetosphere.

are the Norwegian stations at Longyearbyen and Ny Ålesund in the Svalbard archipelago (Sandholt et al., 2002) and at the South Pole Station on Antarctica.

Most electrons responsible for auroral emissions reach the ionosphere after having first been stored and accelerated in a part of the Earth's magnetosphere called the plasma sheet. Until Russian and American satellites discovered the plasma sheet in the early 1960s, its existence was not even theoretically anticipated. It turns out that the plasma sheet is also the source of electromagnetic energy that drives geomagnetic substorms. The exact processes that lead to substorm initiation still remain points of contentious debate. Birkeland's basic intuition was essentially correct. Solar electrons reaching the upper atmosphere create aurorae. However, neither he nor anyone else of his generation or the next understood that auroral electrons first must be trapped and accelerated in the Earth's magnetosphere. Trajectories calculated by Størmer and simulated in terrellas most aptly simulate those of high-energy cosmic rays of solar or galactic origin penetrating the Earth's magnetic field (Figure 14) not auroral particles.

### (b) Birkeland's Field-Aligned Current Hypothesis

The second, albeit implicit, aspect of Birkeland's message from the Sun concerns field-aligned currents that couple the ionosphere to interplanetary space. Magnetic field measurements from the four stations of the 1902-1903 expedition supplemented by data from low to mid latitude observatories allowed Birkeland to infer the existence of two large current systems that flowed at polar and auroral latitudes. Millions of Amperes are needed to explain global magnetic disturbances. Birkeland argued that the responsible currents connect to distant space through magnetically field-aligned currents.

While the ultimate source of these currents must be the Sun, the exact mechanism was for a time left undetermined. In 1960 a magnetometer on the Pioneer V satellite showed that the solar wind is magnetized. The intensity varies from a few nanotesla during magnetically quiet times to several tens of nanotesla during large disturbances. This interplanetary magnetic field (IMF) is weak and is carried away from the Sun by the solar wind. In the Earth's frame of reference the convecting IMF appears to induce an electric field capable of energizing charged particles. The observation of the IMF has had critical consequences for understanding solar control of terrestrial dynamics in the magnetosphere and ionosphere. Soon after the first observations a British scientist James Dungey pointed out that if the IMF has a southward component, it is possible to explain how the solar wind drives the current systems of the high-latitude ionosphere (Dungey, 1961). At the equator on the dayside the Earth's magnetic field is northward. Regions of opposite magnetic polarities merge with each other. Dungey considered three types of magnetic fields. The first is the IMF that is being carried away from the Sun by the solar wind. The second type includes "closed" magnetic field lines with both feet anchored to the Earth. The third type forms when IMF and closed field lines merge on the dayside boundary of the magnetosphere. Two "open" field lines form, each with one foot on Earth and the other in the solar wind. The fast streaming solar wind exerts stresses on these field lines causing them to stretch to form the northern and southern lobes of the Earth's magnetotail. At a great distance (~100 $R_E$) downstream the oppositely directed magnetic fluxes of the two lobes come together and reconnect. Figure 15 indicates that newly reconnected magnetic field lines in the magnetotail are initially stretched. They then snap back toward the Earth carrying with them any attached ions and electrons to form the plasma sheet. The ionospheric footprints of the moving magnetic field lines trace out patterns that mimic Birkeland's current system.

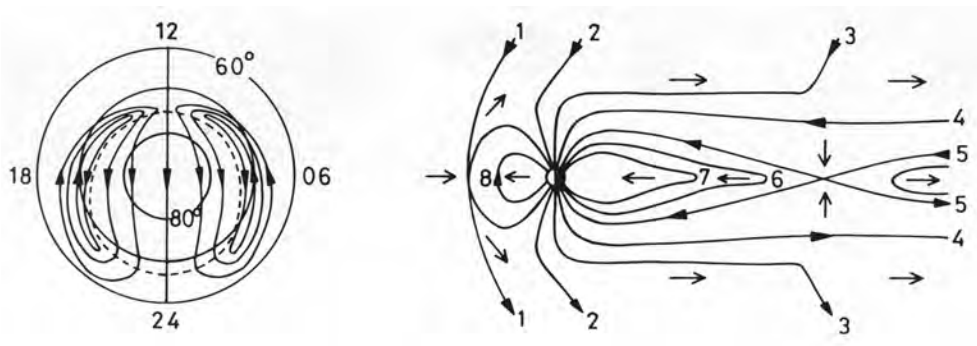



Figure 15: Dungey (1961) model for IMF control of global electrodynamics; (left) ionospheric convection/current pattern and (right) magnetic flux transport in the noon-midnight meridian of the magnetosphere.

As we have seen, Chapman and his coworkers argued that an "equivalent" current system required no field-aligned currents. In assessing this debate Fukushima (1969) realized that with only ground-based measurements it is impossible to decide whether Birkeland's field-aligned currents were present or absent. Still lacking experimental information, space physicists turned their attention to examining the implications of Birkeland's field-aligned current hypothesis. Before discussing measurements of the satellite era, it is useful to consider two theoretical analyses from the 1960s.

Rolf Boström then at the Royal Institute of Technology in Stockholm constructed two detailed mathematical models of auroral arcs and their associated three-dimensional currents (Boström, 1964). The first model assumes that field-aligned currents flow into the ionosphere at one end of an auroral arc and out the other. The second model assumes that field-aligned currents flow in sheets into the ionosphere on the equatorward boundary of the arcs and out along its poleward boundary. The most important contributions of Boström's models were its predictions about variations in the electric and magnetic fields in the presence of field-aligned current driven aurorae. Today we know that both of Boström's models are realized in nature. The first model anticipated what we now call the "substorm current wedge." However, most have the sheet-like field-aligned currents characteristics of Boström's second model.

My dissertation advisor at MIT, Vytenis Vasyliunas considered a variant of the equivalent circuit model and from energy considerations showed that it was unsustainable without field-aligned currents (Vasyliunas, 1968). To understand his argument it first is necessary to reflect on the motions of charged particles in magnetized plasmas such as the ionosphere. Left to their own devices electrons and ions simply rotate in circles around magnetic field lines. If an electric field is applied perpendicular to the magnetic field both ions and electrons execute cycloidal trajectories whose guiding centers move with the same velocity. With no differences between ion and electron drift motions, there would be neither electric currents nor magnetic perturbations.

Ionospheric plasma is created in the upper atmosphere by ultraviolet light from the Sun and/or by incoming auroral particles. The plasma density is at most 1% of the neutrals. The rates of collisions between plasma and neutral constituents increase similarly. Relative to their gyrofrequencies ions undergo many more collisions than electrons. The net effect of collisions with neutrals is that ions primarily drift in the direction of the applied electric field but electrons generally drift perpendicular to both the electric and magnetic fields. The different ion and electron drift velocities generate two electric currents. Currents in the same direction as the electric field are called Pedersen currents. Currents flowing perpendicular to both fields are carried by drifting electrons and are called Hall currents. The "equivalent currents" are mostly Hall currents.

Pedersen currents have consequences for energy balance in the ionosphere and require field-aligned currents. Pedersen currents in magnetized plasmas arise because ions and/or electrons collide with atmospheric neutrals, giving net drifts along the direction of the driving electric field. In these collisions the plasma gives up kinetic energy to the random motion of neutrals. When a current flows through a resistor, collisions between current carriers and the resistor material causes the temperature of the resistor to rise. The process is commonly referred to as Joule heating, named after the English physicist James Prescott Joule (1818-1889). Unless energy is continually fed into the ionospheric circuit the currents will quickly dissipate due to Joule heating losses.

A fundamental relationship governing electric circuits is Kirchoff's law, named after the German physicist Gustav Robert Kirchoff (1824-1887). It requires that all currents in a circuit be continuous. If the equivalent currents were purely of the Hall type, they indeed could flow continuously in the ionosphere. The addition of Pedersen currents necessarily introduces discontinuities, apparently violating Kirchoff's law. Only two options are available. First, the ionosphere cannot act as a steady-state circuit. Current would quickly dissipate, similar to a capacitor discharging through a resistor. The second choice is that the ionospheric circuit is continually fed by magnetic field-aligned currents that connect to "generator" regions in the magnetosphere and/or in the solar wind. Since magnetic disturbances can last for many hours a steady-state circuit must form in which field-aligned currents are necessary to conserve energy.

The detection and identification of magnetic perturbations due to field-aligned currents appear to be far more straightforward in retrospect than in fact. Putting a magnetometer onto a satellite with a high-inclination orbit was a first and necessary step. In 1983 Dessler wrote the following description of their first detection:

> In early 1966, more than half a century after Birkeland had put forth his experimental and theoretical evidence regarding the existence of field-aligned currents, Zmuda, Martin and Heuring submitted a paper to the *Journal of Geophysical Research* reporting the existence of "transverse magnetic disturbances in the auroral zone as measured by a satellite borne magnetometer. I was editor of the space physics portion of *JGR* at the time. I had been attuned to the possibility of the existence of field-aligned currents from listening to Alfvén at several meetings and reading some of his papers, and more importantly, from talking with Carl-Gunne Fälthammer whose arguments influenced me greatly. In addition *Patel* (1965, 1966) reported localized magnetic disturbances measured with the satellite Explorer 12. These too had been interpreted as hydromagnetic waves. Although I was one of the early champions of hydromagnetic theory to explain geomagnetic phenomena, it seemed clear that these localized, low frequency magnetic disturbances did not fit the concept of a propagating wave. Field-aligned currents must cause the disturbances.

Dessler then describes how he refereed the paper himself and suggested that the authors include field-aligned currents as a possible source of the observed magnetic disturbances. When the authors declined his suggestion, Dessler and a graduate student wrote an article for the *Journal of Geophysical Research* arguing that field-aligned currents had finally been detected. Between 1966 and 1970 Zmuda and coworkers published at least four papers on transverse magnetic perturbations. However, it was only in a late 1970 paper by Armstrong and Zmuda, that the group publicly embraced a field-aligned current interpretation of their data (Armstrong and Zmuda, 1970). Why did they take so long? No evidence suggests that they were influenced one way or another by the long debate between the British and Scandinavian schools.

Zmuda's descriptions of the 1963-38C satellite and their onboard magnetometer indicates how difficult it was in the late 1960s to make the precise measurements needed to identify field-aligned currents. At the time many satellites were stabilized with large bar magnets that aligned with the Earth's magnetic field. They also induced a torque that made the spacecraft precess in a cone of $6^{o}$. Their magnetometer could measure only one component of the Earth's magnetic field. In the auroral zone the Earth's magnetic field is ~50,000 nT. Typical magnetic perturbations due to field-aligned currents are a few hundred nT, causing the Earth's magnetic field to tilt by a few tenths of $1^{o}$. The suggestion of Cummings and Dessler (1967) to interpret the cause of the magnetic perturbations as field-aligned currents was both correct and useful. However, the caution exercised by Zmuda's group was prudent and in the long run placed the existence of Birkeland currents on unassailable ground.

Takesi Iijima of the University of Tokyo and Thomas Potemra of the Johns Hopkins University Applied Physics Laboratory used a three-axis vector magnetometer on the TRIAD satellite in a circular polar orbit at an altitude of 800 km to systematize Birkeland currents in the high latitude ionosphere (Iijima and Potemra, 1976, 1978). They discovered a large-scale system of field-aligned currents that is nearly co-terminal with the auroral oval. Along the high-latitude boundary of the auroral oval, sheets of current flow into the ionosphere on the dawn side and out of the ionosphere on the dusk side. Near the equatorward boundary of the oval field-aligned currents of opposite polarities connect the ionosphere to the magnetosphere. The poleward and equatorward systems of field-aligned currents are called Region 1 and Region 2, respectively. Near noon another sheet of field-aligned current develops poleward of a Region 1 current. Its polarity is opposite to that of the adjacent Region 1 current. Its presence or absence on the morning or afternoon side of magnetic noon is controlled by the east-west component of the interplanetary magnetic field. This current is directly tied to interplanetary space and arises in response to stresses exerted on the magnetosphere by the solar wind via open magnetic field lines.

Over the past few years the focus of my space research has returned to the topic of magnetic storms (Huang and Burke, 2004). The Air Force Research Laboratory regularly flies auroral particle detectors, scientific magnetometers and ion drift meters on spacecraft of the Defense Meteorological Satellite Program (DMSP). These satellites fly in polar orbits in such a way that they remain in the same local-time plane (e.g. 06:00 – 18:00 LT). We have developed techniques to use the magnetometers and drift meters as ammeters and voltmeters that probe the field-aligned current circuits. We find that during the main phase of very large magnetic storms the plasma sheet regularly generates very large amplitude field-aligned currents, often in excess of ten million Amperes. The electromagnetic power that these currents carry into the ionosphere (> 500 TW) is many times that of the auroral particles and can even exceed the power of solar illumination reaching the entire dayside of the Earth. This energy radically alters the density and wind structure of the upper atmosphere and can cause space objects such as Skylab to re-enter the atmosphere at unpredicted times and locations. However, due to a quirk of nature discovered by Fukushima (1969), these field-aligned currents produce no magnetic perturbations on the ground. Models that rely solely on equivalent current systems are blind to what is really happening in space.

## Conclusions

Initially Kristian Birkeland's *Message from the Sun* was an alert to the public of his time that the Earth and the Sun were more closely connected than seemed possible. The disruption of telegraph communications during the magnetic storm of September 1898 pointed toward still more critical impacts on ordinary life as we moved into ever more technologically driven societies. In a deeper sense it provided the first roadmap for understanding what Birkeland acknowledged to be a complex relationship. To develop his models further, he had to acquire systematic information about the aurora and geomagnetic disturbances. His pioneering auroral expeditions of 1899-1900 and 1902-1903, interpreted in the light of his laboratory simulations, led him to see that the Sun not only bombards the upper atmosphere with energetic particle to produce auroral light, it also drives the circuit responsible for magnetic disturbances. Seeing magnetic disturbances in terms of a large distributed current system was in many respects the key insight that Birkeland bequeathed to us.

With his abiding love of electromagnetic theory Birkeland would have enjoyed delving into Parker's (1963) model for solar wind acceleration and observing the power unleashed in the magnetic reconnection events as CMEs explode into space. What would Birkeland have thought about the solar dynamics revealed by the Transition Region and Coronal Explorer (TRACE) satellite (Figure 12), or of CMEs imaged by the Large Angle and Spectrometric Coronagraph (LASCO) on the Solar and Heliospheric Observatory (SOHO) satellite (Figure 11) and the Solar Mass Ejection Imager (SMEI) experiment on the Coriolis spacecraft? I expect that Birkeland would eagerly anticipate the launch of two STEREO satellites in the summer of 2006. They will observe the births of CMEs from widely spaced vantages near the progressive and regressive libration points. There they can distinguish CMEs racing toward Earth from those heading safely away. They can view large active sunspots hidden behind the solar limbs and raise alerts when magnetic storms are likely to occur. Knowing the basic correctness of Birkeland's Message from the Sun, our next step is to learn to predict the arrival of storms.

Science, like any human endeavor, does not progress linearly. All possible explanations have to be explored. In the end the weight of experimental information and theoretical understanding separates wheat from chaff. This was a necessary, and often painful, part of our collective reflection on the Message from the Sun. It has been a fruitful reflection that extended over more than a century, leading to a sense of wonder and joy as bit by bit the pieces of the puzzle fit together. We are grateful to Kristian Birkeland for pointing us in the right direction, and to the many scientists, both famous and unknown, who have contributed to the discussion and deepened our understanding of the Sun's message.

## *Acknowledgments*

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Dr. William J. Burke completed his doctoral dissertation "A Theoretical lnvestigation of Small-Scale Auroral Zone Electric Fields" at the Massachusetts Institute of Technology under Professor Vytenis M. Vasyliunas in 1971. He did post-doctoral research at Rice University on the lunar plasma environment and on microwave emissions from natural surfaces at the NASA/Johnson Spaceflight Center. In 1975 he joined the Air Force Geophysics Laboratory where he has contributed to and/or led the analysis of plasma and field measurements acquired by sensors on the INJUN 5, ISIS 1, S3-2, SCATHA, DMSP, DE and CRRES satellites as well as the STS 3, STS 46 and STS 75 shuttle missions.

He also participated in the analysis of data from the beam-emitting sounding rockets BERT, ECRO 7, MAIMIK and CHARGE 2B. He is currently involved in the analysis of data retrieved during active geomagnetic periods by the CLUSTER, CRRES, DMSP, GEOTAIL and POLAR satellites. His analyses of data from the TSS 1 and TSS IR missions empirically specified the circuit characteristics of electrodynamic tether systems.

He frequently serves as a consultant for NASA headquarters regarding solar-terrestrial interactions and chaired the 2000 Senior Review of its Solar Terrestrial Program. He has authored/co-authored more than 200 peer-reviewed scientific papers on space weather effects. He is a fellow of the Air Force Research Laboratory, a distinction allotted to less than one percent of its scientific staff

**The Birkeland Lectures 1987 – 2005**

1987: Hannes Alfven, Kungliga Tekniska Høgskolan , Stockholm, Sverige:
***"The Auroral Research in Scandinavia"***
*(University of Oslo, Norway, 3. September 1987)*

1988: Alex J. Dessler , Rice University, Housten, USA:
***""I have it" - Birkeland´s quest for research founding"***
*(University of Oslo, 16. June 1988)*

1989: T.A. Potemra, The Johns Hopkins University, Laurel, Maryland, USA:
***"Satelite measurements of Birkeland currents"***
and
Naoshi Fukushima, Tokyo University, Japan:
***"Birkeland´s work with the geomagnetic disturbances in relation to modern research"***
*(The Norwegian Museum of Science and Technology, Oslo, 4. October 1989)*

1990: James van Allen , University of Iowa, USA:
***"On the future of space science and applications"***
*(University of Oslo, 11. October 1990)*

1991: Syun-Ichi Akasofu , Geophysical Institute, Fairbanks, Alaska, USA:
***"Helio-magnetism"***
*(University of Oslo, 24. October 1991)*

1992: W. Ian Axford , Max-Planck Institut, Lindauer, Germany:
***"The origin of cosmic rays"***
*(University of Oslo, 24. September 1992)*

1993: Takasi Oguti, Solar-Terrestrial Environment Laboratory, Tokyo, Japan:
***"Sun-earth energy transfer"***
*(Tokyo University, Japan, 7. October 1993)*

1994: Stanley W.H. Cowley, Imperial College, UK:
**"The Solar wind – Magnetosphere-Ionosphere connection"**
*(The Norwegian Academy of Science and Letters, Oslo, 22. September 1994)*

1995: Anthony L. Peratt, Los Alamos National Laboratory, USA:
***"The legacy of Birkeland´s plasma torch"***
*(University College, Notodden, Norway, 21. September 1995)*