KRISTIAN BIRKELAND: THE GREAT NORWEGIAN SCIENTIST THAT NOBODY KNOWS

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Introduction
Ask a foreigner for the name of a famous Norwegian. Rapidly one discovers that the late nineteenth century produced a flowering of Norwegian cultural talent as, as likely as not, the nominee will come from that time. These were, of course, years of an increasing sense of Norwegian identity, the years leading up to Norway's independence from Sweden in 1905. The list of Norwegians easily identified by a foreigner would surely include Henrik Ibsen, Edvard Munch, Edvard Grieg, Fridtjof Nansen, Roald Amundsen. However, one man would be missing. Despite being featured on the tail planes of Norwegian airliners and familiar to Norwegians after featuring for 20 years on the 200 NoK banknote, Kristian Birkeland will not leap to foreigners' minds. Even if you asked for a scientist, one might get Abel, Lie or Bjerknes before Birkeland. Why is that so? Here I shall attempt to explain this conundrum. A detailed biography has been given by Egeland and Burke (2005). In addition, an English journalist (Jago, 2001), has written a biography that is almost a novelisation of his life. That this could be done, marks how multifaceted this man was. Birkeland was obsessed with the Northern Lights. The elegant picture in Figure 1 illustrates this, and Jago brings out this clearly. Egeland and Burke, both scientists, make clear how close he came to understanding their origin. I'll try not to repeat too much of what is told in the two books.

A short life history
Kristian Birkeland was born 150 years ago in Kristiania, which was to become Oslo. He died exactly 100 years ago on June 15th 1917 on the other

Figure 1: This composite of a portrait of Kristian Birkeland and the aurora borealis over Longyearbyen, Svalbard represents visually Birkeland's obsession with understanding the Northern Lights. Credits: Illustration: Hanne Utigard. Photo of Birkeland: Ludvig Forbech-MUV /UiO. Northern lights photo: Yngve Vogt.

side of the globe in Tokyo. His exceptional nature showed early on. His father was an import/export merchant and gave him a comfortable family background. He was an outstanding student. After university in Kristiania, in 1893, he left to go to Paris and the Ecole Polytechnique where his primary interest was in the new science of electromagnetism coming from Maxwell's equations. Stints follow in Geneva, Bonn, where he met Hertz, the man who discovered electromagnetic waves, Leipzig, and he then returns to Kristiania (Oslo) to become the youngest professor at the university.

A charming picture that we have of him at this stage in his career is due to the eccentric activity of one of his early students, Carl Størmer, who wandered the Karl Johans Gate with a concealed camera. Størmer's collection of snapshots provides overall a trip back to the late 19th Century. Elegant young ladies, for whom as subjects it seems Størmer had a predilection, stroll along with parasols, bustles and exotic hats. Young men, nearly always greeting Størmer with hats formally raised, stroll along the fashionable street unaware of the deception. Well known people are recorded this way including Henrik Ibsen, the playwright, and Ivar Aasen, the botanist/linguist. The young professor Birkeland is an exception. Størmer captures him in three photographs, coming out of the old University building and then crossing towards the photographer. In Figure 2, the final snap, you can almost imagine that the professor is greeting the student with hand outstretched. Not so! As Størmer later revealed, Birkeland was the only person who detected the ruse and he was outraged. Ironically, as we shall see, Carl Størmer was given a research problem by Birkeland that would effectively occupy Størmer for a large amount of what became an eminent career. Indeed, it is fair to say that Størmer's standing in the Anglo-Saxon world exceeded Birkeland's until well into the late 20th Century.

Part of the problem of recognition may lie in the man himself. Was he a scientist, a physicist or a geophysicist, an explorer or a prolific inventor or even an entrepreneur? One thing is clear his capacity in physics was great. In 1897, J.J. Thompson made his discovery that the rays were negatively charged particles, electrons. Before this, whether cathode rays were an electromagnetic wave or a particle was highly unclear. Birkeland did experiments to show that the rays did experience a magnetic force. Even as Thompson was formulating his discovery, Birkeland was wondering if the aurora could be due to the rays and whether the Earth's magnetic field had a part to play in what was seen in the sky (Egeland and Burke, 2005).

Figure 2: *A photograph of Kristian Birkeland in 1895. Photograph taken using a concealed camera by Carl Størmer. Photo: Oslo Bymuseum.*

Never one to see the boundary between theoretical and the experimental side of physics, Birkeland decided to mount an expedition to Finnmark in the very north of mainland Norway to observe the aurora. The expedition established an observatory at Haldde, but was not a success due to very extreme weather which lead to the death of one member, E. Boye. In 1899, he repeated his attempt, and there was success. The aurora was determined not to be a meteorological effect, but was established to occur at an altitude close to 100 km above the Earth's surface far above the level of the clouds. The method of deducing the height is shown in the sketch in Figure 3. At the same time the phenomenon is shown to have a magnetic response on the

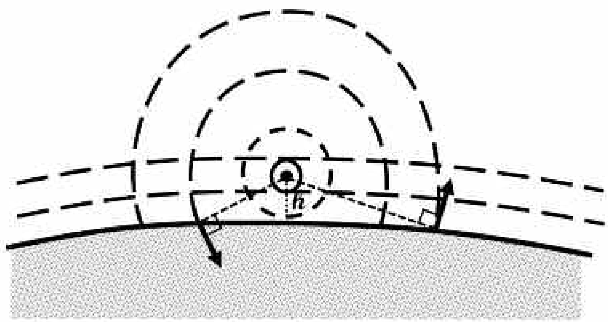


Figure 3: Illustration of estimating the height of an electrical current flowing horizontally (out of the page) in the upper atmosphere (now known as the ionosphere). The dashed lines circles represent the perturbation field of the current and arrows represent the perturbation field detected at stations north and south of the current. The height h was found to be of order 100 km. Sketch derived from Egeland and Burke (2006) p. 70. The actual situation is complicated by the conductivity of the Earth.

ground produced by electrical current flowing horizontally in the vicinity of the arcs of light. A further expedition in 1902–3 is even more ambitious, and much is established about auroral morphology that stands today.

The idea that the electrical nature of the aurora means it is in some way connected with the newly discovered sub-atomic particle, the electron, would not leave Birkeland. Moreover, the extreme height at which the aurora occurs, suggests a cosmic origin. Ever happy to enter the laboratory, Birkeland also set up a practical experiment with a magnetised sphere in a vacuum chamber where he bombards the sphere with electrons. He called the experimental set up a terrella, using a term first introduced by William Gilbert

(Gilbert, 1600) in his 15th Century treatise on magnetism. The electrons orbits in the sphere's magnetic field cause them to cluster in rings around the two poles of the sphere. The resemblance to the morphology of the actual aurora was striking. It also occurs not exactly at the poles, but in zones surrounding the magnetic poles of Earth.

Carl Størmer, who had a mathematical bent, started work with Birkeland on calculating the trajectories of the charged particles in the dipole magnetic field of the terrella. In his career Størmer would also publish a great deal of pure mathematics (and he became professor of mathematics at the University of Oslo), but the aurora remained his passionate interest. He continued participating in observational work. Ironically, his mathematical solutions for charged particle trajectories in a dipole field we know today do not illuminate much about the aurora. However his work became fundamental for understanding the behaviour in the Earth's field of the very high energy cosmic particles known as cosmic rays. When I joined a cosmic ray research group for my PhD in the mid 60's, the laboratory had a terrella. Ironically, in those days, the name Birkeland was not mentioned, but Størmer's work was well-known.

Birkeland submitted a paper to the British scientific journal, *Nature*, proposing that streams of electrons from the Sun are the source of the aurora. It was passed to Arthur Schuster, professor of physics at the University of Manchester to review. Schuster pointed out that such a stream would cause the Earth to charge negative, and the resulting electric field would quench the stream. Birkeland's reaction to the (correct) criticism at the time is not known, but he did not resubmit his paper to *Nature*. Nevertheless, it is clear that he took the criticism on board; in his report on the third expedition of 1902–3 he includes a revised idea that charge neutral streams of positive and negatively charged particles come from the Sun to drive the aurora (Birkeland, 1908). Schuster must have communicated directly with Birkeland as Birkeland gives an explicit response in the report. Sadly, this result appears to have been missed by the British scientific community as we shall see. If Birkeland's modified story had been widely read and accepted by the interested scientific community, almost certainly the history of our understanding of solar terrestrial relationships would have been very different. Although described clearly enough in the expedition report, it did not have the impact on scientific thinking that a *Nature* paper might have done.

The report of the expeditions work published in 1908 includes a sketch like the one reproduced in Figure 4 (Egeland and Burke, 2010). Annotations have been added. Diagrams such as this showing downward current entering

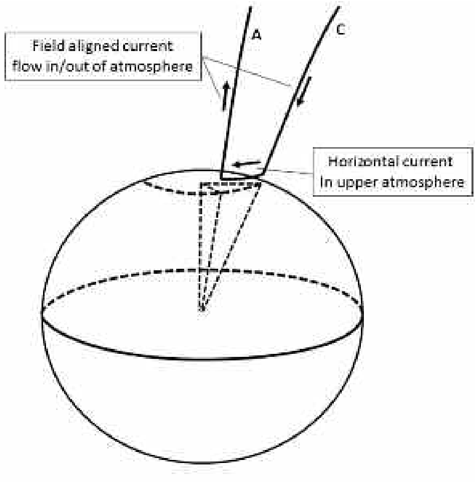
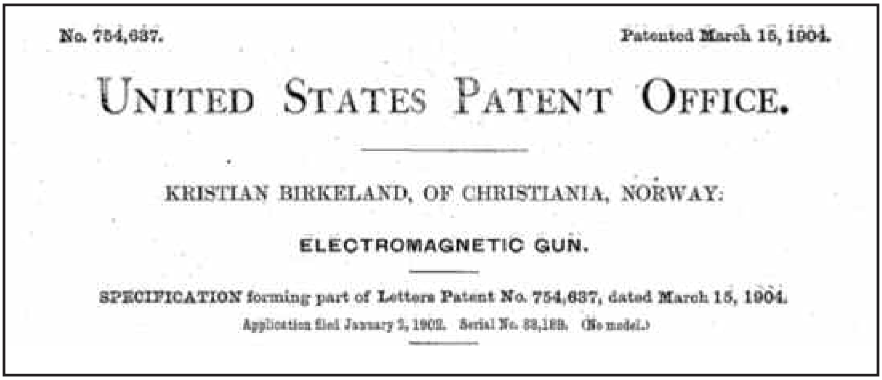


Figure 4: The sketch reproduced and annotated from that shown in Egeland and Burke (2010) which they had reproduced from the original is in Birkeland (1908). Current flows down one field line (C) into the upper atmosphere (now the ionosphere) and out of the atmosphere on field line A. Horizontal current is driven East-West in the auroral zone. It is implicit that there is a voltage (or EMF, electromotive force) between A and C.

the upper atmosphere at one longitude, flowing through horizontally and leaving by an upward return current at a separate longitude are now common place. Birkeland had made the first sketch of the three-dimensional electrical current system of an auroral disturbance. The sketch would be recognised today.

We shall return to the origin of the aurora shortly. After his 1902–3 expedition Birkeland still needed money for his auroral research and, like other scientists have done, he started looking at military applications of his work. Governments may be parsimonious when it comes to pure science, but in unstable times money is often available for work on defence. In a period when tensions were building between nations in Europe, he designed and built a prototype electromagnetic gun. He submitted a US patent application, illustrated in Figure 5. As with his auroral ideas he was well before his time. In the 1980's his idea was to be taken up within the American "Star Wars" defence initiative of President Reagan. No doubt in order to raise capital, he arranged to make a demonstration in the Domus Academica of the Kristiania University. The gun had worked successfully in tests, but the public event descended in to farce as a short circuit caused a large electrical discharge and a loud explosion.

The local newspapers had a field day making fun of Birkeland. A lesser man might have died of shame. If he was unlucky in this, the event was followed by a very lucky occurrence. Within a short time, he meets socially an entrepreneur, Sam Eyde. Eyde has realised that Norway has a particular asset



No. 754,637. Patented March 15, 1904.

UNITED STATES PATENT OFFICE.

KRISTIAN BIRKELAND, OF CHRISTIANIA, NORWAY.

ELECTROMAGNETIC GUN.

SPECIFICATION forming part of Letters Patent No. 754,637, dated March 15, 1904.

Application filed January [illegible], 1902. Serial No. [illegible]. (No model.)

Figure 5: The title page of Birkeland's US Patent from 1904

in its combination of high mountains and much precipitation. Vast amounts of energy are released by water in waterfalls. Hydroelectric plants are being introduced all over the world. However, supplying Norway with electrical power is not all Eyde is thinking about. He knows that lightning can break up the molecules of nitrogen, the primary but largely inert gas in the air. Nitrogen atoms can then combine with oxygen and form nitrates. Nitrates are critical for fertilising the soil. Farmers world-wide were increasingly using nitrate fertilisers. The major source of nitrates for such use was the large guano beds of Chile. If only one could bottle lightning, Eyde knows that there would be an important market to gain. Eyde remarks along these lines to Birkeland. Birkeland echoes Archimedes by responding with the phrase "I have it". He realised that the unintended discharge from the gun is an example of artificial lightning and it surely could be done in a controlled manner. The seeds of what was to become the largest company in Norway, Norsk Hydro, now known as Yara, and today operating in more than 50 countries were thus sown. The gun is put on one side, and work starts on building a plant to produce artificial fertiliser with capital provided by the Wallenberg family.

The critical time in the development of the fertiliser project was in 1905. As Egeland and Burke describe, Birkeland decided to get married in the May of that year (Egeland and Burke, 2005). He seems to have taught a class at the university on his wedding morning, an act that was eccentric enough. Even more unusual is that what passed as a honeymoon was spent at the fertiliser plant site of Notodden. The marriage did not last. As we've already noted, the fertiliser project and the company it seeded did.

In 1909 the Birkelands eventually divorced although they separated long before (Egeland and Burke, 2005). Birkeland's frenetic work not only no doubt destroyed the marriage but also was beginning to take a toll on his own health.

In 1903 the Bayer Company had introduced a pharmaceutical product to aid relaxation and sleep called Veronal. It was an early barbiturate based drug. Barbiturates are notoriously dangerous as they can be addictive, and excessive dosage is easily fatal. With his extreme work schedule, Birkeland started taking Veronal at some point. Barbiturates like Veronal can induce hallucinations and paranoia. The trolls were gathering.

Early in the second decade of the century, he was in a state of exhaustion induced by the combination of the failed marriage and the pressure of producing the great final report of his auroral expeditions, which was published finally in 1913. A warmer climate seemed sensible. Moreover, he had a scientific problem that would lure him to the South, that of the origin of the zodiacal light. The light that brightens the sky around the ecliptic plane is now known to be caused by sunlight reflected from small dust particles. Birkeland thought electromagnetism might be involved, and he took leave of the university for a year and headed to the Egypt and the Sudan.

Birkeland made his headquarters in Helwan, Egypt, but observations were made further south in the Sudan. While he was there, World War I broke out. His junior assistants were recalled to Norway to join the army. During this period, Birkeland became increasingly paranoid. A letter by Gerda Thomsen (Egeland and Burke, 2005), who had been asked from Oslo to investigate locally how he was, makes clear his paranoia. He was particularly obsessed about the British whom he suspected of spying on him because of his electromagnetic gun. As both Egypt and Sudan were effectively under British control at the time, it was not impossible to see Englishmen everywhere. However, it is unlikely that a country deep in the grip of a world war was going to be too troubled by an isolated scientist in an area far from the main conflicts, whatever past work he had done. Nevertheless, convinced that the British spies were following him, he eventually left and made his way to Japan en route eventually to Norway. However, it is now 1917 and the Russian revolution has broken out, effectively closing the Trans-Siberian rail route to Europe. He has friends in Tokyo and settles in the Seiyoken hotel in Ueno Park. The hotel building is still extant and when last I checked it, is a restaurant. It is here that, either by design or accident, he took a substantial overdose of Veronal which proved fatal.

His death was marked in Norway and his achievements celebrated. Should this recognition not be the end of a sad story? Perhaps it should. Nonetheless, it continues for a further 50 years.

Nemesis

We now need to introduce the nemesis. Sydney Chapman, a mathematician who had been a stellar student at the Universities of Manchester and Cambridge, was only 29 years old and so quite early in his career when Birkeland died. Like Birkeland he had been a prodigy at school and university. In 1917, he had been teaching at Cambridge but, being from a Quaker background he was a conscientious objector. With the advent of conscription to the British Army, he had moved to the Royal Greenwich Observatory where he had been an assistant some years before. The alternative would likely have been prison. There he set to work on using the large amount of geomagnetic data from around the world to classify the forms of geomagnetic disturbance. He produced three indices describing separate magnetic disturbance effects, S_q, for the quiet diurnal variation, S_d, the local time dependent storm time variation and Dst, the longitude independent storm time disturbance (see e.g. Soon and Yaskell, 2003). Birkeland had also identified a similar three-way classification (Birkeland, 1908) but it is Chapman's designations that are known today.

Chapman published his work in 1918 (Chapman, 1918). In fact, despite his youth, Chapman's career was about to take off. In 1919, he was appointed to a professorship in Applied Mathematics at Manchester University. In the same year he was elected to the Royal Society, no doubt in part for his work on geomagnetism. Chapman's paper on statistical analysis of geomagnetic disturbances concluded with a short theoretical speculation suggesting that geomagnetic storms were occasioned by a stream of electrons from the Sun, exactly as Birkeland had done more than a decade before (Ferraro, 1969; Southwood, 2015). I learnt this from Vincent Ferraro who was my undergraduate tutor. Ferraro had been a student of Chapman's during the long period in the 20's and 30's when Chapman was mathematics professor at Imperial College. Even in the 60's Ferraro was much in awe of Chapman.

Unlike Birkeland, Chapman had actually published the false notion of a stream purely made up of electrons, and it was Frederick Lindemann (1919) who pointed out publicly that the theory could not work because of the electrostatic forces that would build up and quench the flow. Scientists do not like to get things wrong and that alone is embarrassing. However, as Chapman's career was beginning to flourish it must have been doubly so. The mistake is basic. Moreover, as Ferraro (1969) indicates, there had been some numerical development of the theory. Chapman's feelings must have been severe.

I met Chapman several times when I was a student. He seemed to me a very polite, if a little over-serious, rather as one might expect someone with a Quaker upbringing to be. By the late 60's he was held in enormous regard. I attended an 80th birthday conference where numerous of his old students spoke, most of them themselves giants. With hindsight, I recall that each seemed to have kept to a particular discipline; I suppose that might indicate that the grand old man kept his acolytes under control. Human beings are odd, and who can securely state what caused any particular behaviour? Nevertheless, of all reasons advanced for Chapman's antagonism towards Birkeland and his ideas, the most likely for me comes from the story recalled by Ferraro. I think it provides the psychological root of the antipathy to Birkeland that Chapman exhibited for the next 50 years.

In the early thirties, Chapman and Ferraro in a series of papers (Chapman and Ferraro, 1930; 1931; 1932) did use the idea of the release of a neutralised stream of positive and negatively charged particles from the Sun marking the start of a geomagnetic storm. In sharp contrast with the assumption of Birkeland, they assume the stream is unmagnetised and as it is perfectly conducting it confines the terrestrial magnetic field inside a cavity (the latter now called the magnetosphere). The mathematics of the formation of the boundary was solved using a simplified planar model of the stream front. The theory gives a satisfying explanation of the initial storm phase where the field (and the Dst index) at the Earth's surface rises. It gets nowhere in explaining the subsequent depression of field (and Dst) as a ring current builds up inside the cavity. This model nonetheless was widely appreciated as a start on understanding solar-terrestrial relations.

The Champion

The Chapman-Ferraro model was not accepted in one quarter. The swedish scientist, Hannes Alfvén, 20 years younger than Chapman, was not convinced by the Chapman-Ferraro model. He became a champion for Birkeland's ideas on solar terrestrial coupling. Unfortunately, Chapman was not impressed by Alfvén. In 1938, Chapman with Ernest Vestine (Vestine and Chapman, 1938) published a paper that compares the Chapman model of horizontally confined geomagnetic currents rather unfairly to Birkeland's (1908) model. Fukushima (1991) analyses this paper thoroughly. He expresses puzzlement as the Birkeland system used is not really what Birkeland would have had for a global model. Indeed the paper reads as if the authors are determined that currents only flow horizontally, and the paper concludes with a vague discussion that storm time disturbances must have an upper atmospheric auroral heat source as the dynamo, something that is certainly not justified by the content of the paper.

The paper must have outraged Alfvén. Shortly afterwards, in the early years of World War II, Alfvén (1939, 1940) published a theory of magnetic storms that, in having a magnetised stream of neutral material from the Sun, was much closer to Birkeland in spirit. Alfvén had difficulty publishing his work, and the papers appear in the rather obscure Proceeding of the Royal Swedish Academy; he felt Chapman was behind this. Certainly, a rebuttal of his work appeared rapidly from one of Chapman's collaborators (Cowling, 1942) in a leading journal. With hindsight, both theory and rebuttal are wrong.

Alfvén did not give up. Once the war was over, he came to UK in 1946 and went to visit Chapman who had just moved from Imperial College to Oxford. In 1977, Alfvén told me about this visit as I recounted it in a paper in 2015 (Southwood, 2015). Chapman meets Alfvén from the train from London and, having established that this is his first visit to Oxford then leads him on a tour of the sights with Alfvén begging to talk about his theory. The day ends with Chapman seeing Alfvén back on the train and responding to his plea to talk about his theory by saying: "Maybe next time." I was concerned that he might only have told me the story and I thought that, whether it was precisely true or not, it indicated the antipathy between Anglo-Saxon and Scandinavian schools at that time. I have recently been delighted to learn that Alfvén did commit the story to paper and so there is documentary evidence. Alv Egeland has told me he has a copy of a letter from Alfvén to Alex Dessler that recounts the story.

Despite the fact that Alfvén's effective invention of magnetohydrodynamics led to enormous advances in astrophysics and plasma physics in general in the 1950's and 60's, there was a division of the community into Scandinavian and Anglo-Saxon schools, particularly on issues concerned with solar terrestrial coupling and the aurora.

To see the dichotomy, it is good to start from the backgrounds of Chapman and Alfvén. A romantic view would be that both Birkeland and Alfvén from childhood would have seen the dynamic nature of the Northern Lights in the sky, whereas in Greater Manchester one of the dampest and most industrialised areas of England where Chapman grew up, clouds or fog would have been the norm. However, as much as anything, it seems to me more likely that Chapman's austere Quaker upbringing might have been more important. In contrast with the Scandinavians, Chapman's approach was always accumulation of data and drawing out statistical descriptions. Then came rigorous mathematical analysis. Indeed, Chapman was fundamentally a mathematician. Alfvén was originally an electrical engineer. Birkeland was probably best described as that rare bird, an applied physicist endowed with a strong grasp of theory.

Two issues lie at the core of the dispute. Chapman thought that current flow between space and the ionosphere was unimportant, and that the presence of a magnetic field in interplanetary space was not significant. Alfvén opposed him on both counts. In the final analysis Alfvén (and Birkeland, by extension) was right in each case.

There is a simple rigorous mathematical basis for ignoring vertical currents. It is a technical mathematical fact that if one attributes a map of geomagnetic disturbances measured on the Earth's surface to a system of currents flowing in the ionosphere, there is no way to identify where current might flow in or out into space. Although the result is sometimes attributed to Fukushima (1969), I am fairly sure that Chapman knew it and accordingly (and correctly) insisted on using the term equivalent ionospheric current system for his model current systems. Somehow he later was led to the view that vertical currents did not occur and to ignore the possibility that the vertical sheets of the aurora might be associated with vertical current flow. For Birkeland, currents flowing along the magnetic field were fundamental to the process. In particular, an electrical engineer like Alfvén looking at a sketch like that in Figure 4 would immediately see that there needed to be a potential difference between the upward and downward current. Where this voltage had its source, would be the source of energy. For Birkeland (and Alfvén) that source was manifestly cosmic and associated with the Sun. When the ionospheric currents are generated by thermal or tidal stresses in the ionosphere itself, the issue does not arise. However, in geomagnetic storms, there is a direct material coupling between the solar environment and the upper atmosphere, and the currents flowing in and out of the ionosphere are an essential feature. The mathematical uniqueness theorem that underpins the equivalent current notion has no value once data came from above and below the layer where horizontal currents flow, i.e. once the space age had begun, such data would appear. The space age began in 1957 with the launch of Sputnik by the USSR under the auspices of the International Geophysical Year (IGY). Ironically, Chapman had, with Lloyd Berkner from USA, initiated the IGY in the early 50's and steered the global effort throughout.

In 1967, ten years into the space age, the Norwegian Academy of Science organised a major symposium to mark the centenary of Birkeland's birth. By then, Sydney Chapman was the best known of solar terrestrial scientists. His major contributions in many fields of aeronomy, geomagnetism and solar physics were unquestionable, and it was natural to ask him to provide a keynote speech. Unexpectedly, that address and the accompanying written paper that was published in the proceedings, laid bare the gap in understanding between Anglo-Saxon and Scandinavian schools.

A postgraduate student at the time, I did not attend the Birkeland symposium. However, Chapman's keynote talk (Chapman, 1968) was published in the conference proceedings (Egeland, A., and J. Holtet, 1968).

One quote is enough here: "Though Birkeland was certainly interested in the aurora and devoted a great effort to organization and support to expeditions to increase our knowledge of it, it must be confessed that his direct observational contributions were slight …" The text continues in a very patronising manner. According to eyewitnesses, such as Alex Dessler (now of Texas A&G) and Gordon Rostoker (University of Alberta), Chapman's spoken presentation had been even more severe in its put-down, and the audience were stunned. Why had this occurred? Cowling's (Cowling 1971) biographical memoir of Chapman describes him effectively as having a kind, polite and rather genteel nature. That squares with my own experience.Despite my being a student on the few occasions I met him, he always treated me with respect and interest.

It has been claimed as an explanation that his attitude to Birkeland was because Chapman was xenophobic. That is hard to believe of someone who travelled endlessly and had students from all over the world. Others have suggested that he was something of an imperialist blimp. This does not fit with someone who was a conscientious objector in the World War I and housed and aided resettle refugees from Nazism in the 30's.

I think that the attitude to Birkeland is a personal psychological issue and goes back to anguish about the error in the theoretical appendix of his storm paper of 1918. The timing at the point where he was about to get his first chair and also election to the Royal Society, must have been painful. In a fascinating comment, in his biographical memoir Cowling attributes the 1918 error to "following Birkeland" (Cowling, 1971). This cannot literally be true. Birkeland's error was never published. One is led to suspect that Schuster must have told Chapman of the content of the rejected manuscript, and somehow that became conflated into the implication that Birkeland had led him astray.

In an almost fairy tale ending, Birkeland 50 years after his death, finally achieved his comeuppance over the Englishman. In 1966, Zmuda et al. (1966) reported magnetic field measurements from 1100 km altitude above the auroral zone. An American defence spacecraft (prosaically called 1963-38C) detected localised magnetic disturbances above the terrestrial auroral zone. The magnetic perturbations were interpreted in the first report as due to magnetohydrodynamic waves. However, Cummings and Dessler (1967) recognised that the disturbances really had to be the electrical currents flowing between space and the upper atmosphere in the aurora just as Birkeland had predicted. They referenced Birkeland's 1908 report. In that same year, a paper by Alfvén (1967) based on a talk in 1965 presciently pointed out that testing of the Chapman horizontal current model for geomagnetic disturbances needed to be a priority for testing in space. It was clear that Alfvén expected Birkeland to be proven correct. It is very appropriate that Alfvén and Dessler were the first two Norwegian Academy of Sciences Birkeland lecturers (in 1987 and 1988, respectively).

Chapman did realise his unjust behaviour. Southwood (2015) quotes from Chapman's student Akasofu about a letter he received in 1969 about the field aligned currents that everyone now regards as a fundamental feature of the solar terrestrial interaction. "*Chapman mentioned in his letter to me on 13 April 1969, 'the history of studies of geomagnetic disturbances is a tangled skein,' and he continued '– but I did overlook something (a three-dimensional current system, the author's insertion) to which I was blind and they (Birkeland and Alfvén, the author's insertion) saw. Perhaps people listened too much to me'–.*"

The largest irony is that what became the standard model for solar-terrestrial interaction where the interplanetary field is critical and which inherently contains field-aligned flow from space into/out of the ionosphere, had already been published in 1961 (Dungey, 1961). It would take almost twenty years to gain general acceptance. It is a kind of hybrid of Chapman and Birkeland pictures and, appropriately was derived from Dungey realising (whilst stirring coffee in a Montparnasse café, see Dungey [1983]) how an ionospheric flow driven from outside the magnetosphere by the solar wind would reproduce the S_d disturbance pattern originally derived from ground records by Chapman.

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