1
Pioneers of Electric Currents in Geospace

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ABSTRACT

This review shows that the progress of our understanding of the electric currents in geospace has gone through a progressive development from the time of the Enlightenment in the early eighteenth century to the Space Age in the 1970s. When it was found that magnetic field variations were caused by electric currents in the upper atmosphere, important steps were made in the late part of the nineteenth century. The aurora borealis was believed to be an electric phenomenon by several authors as early as the 1750s. The current system linking the creation of the aurora became a main field of interest in the beginning of the twentieth century and has remained so until our time. At present, we have a large variety of instruments and methods such as satellite and ground-based experiments of different kinds and capacities as well as dedicated computer models to study these current systems further. What appears to be lacking, however, is a more detailed knowledge of the variation of the ionospheric conductivities in space and time.

1.1. INTRODUCTION

Geospace is often used as a denotation of the space between the Sun and the Earth. Solar wind plasma is streaming through geospace and due to the omnipresent magnetic field, electrons and positive ions blowing with the wind are forced to move in different directions with electric currents as an outcome. These electric currents forming in the magnetosphere are connected to the ionosphere of the Earth by field-aligned currents that are closed by horizontal currents in the upper atmosphere. The effects on ground caused by these currents have been a challenge for humankind for generations. This chapter will give an overview of the development of our understanding of these electric currents in geospace from the time of the Enlightenment until the 1970s. Important milestones reached in the eighteenth century like the understanding of the relationship between the occurrence of aurora borealis and magnetic field fluctuations, as well as the fact that the aurora is an electrical phenomenon, are elucidated. The important recognition in the last part of the nineteenth century of diurnal magnetic field fluctuations being a result of electric currents in the atmosphere is emphasized. The introduction of cathode rays and electrically charged particles from the Sun being the cause of the aurora, field-aligned currents, and magnetic storms are given a broad coverage including experimental mapping and models of the current systems involved.

It is expected that the multidimensional European Incoherent Scatter Radar EISCAT_3D system in Scandinavia together with modern space-borne technology will improve our ability to better understand the cause and connections of the electric currents in geospace.

1.2. AURORA BOREALIS AND VARIATIONS IN THE EARTH'S MAGNETIC FIELD

We are all standing on the shoulders of somebody. When we are tracing the pioneers of our field, we have to make a choice where to start. *Chapman and Bartles* [1940]

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claimed that Sir Edmund Halley was the first to publish an observed connection between the aurora borealis and magnetic storms in London on 17 March 1716. From these observations, Halley concluded that the position as well as the shape of the aurora was strongly controlled by the magnetic field. Furthermore, Halley presented the idea that the aurora was due to a magnetic effluvia that streamed out from pores in the Earth's surface and by following the magnetic field lines reached far away from the surface of the Earth, where the ether became luminous [*Halley*, 1716]. Although Halley did not relate his observations to electricity, it might be natural to start this review by mentioning his contributions to the field as they lifted the understanding of the auroral phenomenon from speculative ideas to a frame of reference based on natural science. Furthermore, the aurora borealis is a reasonable introduction to the field as its striking appearance has inspired many scientists throughout history to relate it to electric currents in geospace.

It has been said that the watchmaker George Graham (1673–1751) in London was the first to observe a relationship between the aurora borealis and the variations in the magnetic needle in 1722 [*Chapman and Bartels*, 1940]. In his paper, however, Graham reported peculiar variations in the direction of a magnetic needle. As he described his experiment and dismissed any possible artificial disturbances in his instrument that could explain the remarkable observations, he wrote:

> "I am well assured these Changes in the Direction are owing to some other Cause than Friction of the Needle upon the Pin; but what that Cause is I cannot say, for it seems to depend neither upon Heat nor Cold, a dry or moist Air, clear or cloudy, windy or calm Weather, nor the Height of the Barometer" [*Graham*, 1724–1725, 96–107].

Clearly there was an outside cause of the variations, and in hindsight it is tempting to assume that it must have been at a time of occurrence of northern lights.

Later on, however, the Swedish astronomer and physicist Anders Celsius (1701–1744) probably became the first to have realized a relationship between the aurora borealis and variations in the position of the magnetic needle as he encouraged Olav Peter Hiorter (1696–1750) to look for a possible connection between the occurrence of these two phenomena. Hiorter meticulously made 6638 readings of the position of the magnetic needle from 19 January 1741 until 19 January 1742. When he reported his work in 1747, he had made 10,000 observations and he wrote:

> "But who would have been able to imagine that the northern light had anything in common and a relation to the magnetic needle, and that the northern light when it passes past zenith towards south or accumulating near the western or eastern horizon would cause a considerable perturbation of the magnetic needle amounting to several degrees within a few minutes?" [*Hiorter,* 1747, 27–43].

The first time Hiorter noticed the relation between the northern light and the position of the magnetic needle was 1 March 1741. A few weeks before that, Celsius had written to Graham in London to encourage him to watch the needle, hoping that if a disturbance happened in Uppsala, one could observe whether a similar event occurred at the same time in London, and if so, one could disregard any artificial error source in the local observatories. On 5 April 1741, Graham could report on a variation in London that occurred at the same time in Uppsala and he wrote:

> "The alterations that day were greater, than I had ever met with before. Tho' no alteration of any thing in the Room could occasion it. …the only thing in which I am certain, is, that there was no change of position of any thing in the Room, that could cause it, being alone the whole day" [*Hiorter*, 1747, 36].

Hiorter certainly reverenced Celsius as he submissively summarized his work in the following way:

> "Thus I am glad to ascribe this discovery completely to the late Professor Celsius alone, …and who made it possible for me to continue these researches and to publish these discoveries which otherwise would have been buried with him" [*Hiorter*, 1747, 43].

Johan Carl Wilcke (1732–1796) was a German who came to Uppsala as a student in 1749, and devoted himself to studies of electricity and caloric theory. He also followed up on the work by Celsius and Hiorter as he in 1777 wrote a paper about the diurnal and annual variations of the position of the magnetic needle, and stated:

> "The relationship between the magnetic needle and the northern lights is so clear, common and for good that no one that with attention is watching both phenomena, can have any doubt about it.…The matter is exactly as Mr. Hiorter has described so clearly. The northern end of the magnetic needle seems to follow the auroras and to be attracted by them" [*Wilcke*, 1777, 274–300].

Then Wilcke discussed the auroral corona or "*Norrskens-Solen*" and stated that:

> "The flames of the northern lights are stretching themselves up along the direction that the Magnetic-force is directing the magnetic needle when it turns freely" [*Wilcke*, 1777, 299].

1.2.1. The Aurora Borealis as an Electric Phenomenon

In 1897, the director of the French Meteorological Institute Alfred Angot (1848–1924) wrote in his book *The Polar Aurora* that the French physicist John Canton (1718–1772) appears to have been the first physicist that "pointed out in 1753 the close analogy which auroras offer with the light of electric discharges produced in very rarefied air" [*Angot*, 1897, 158].

This may well be true, but in 1752, the Norwegian bishop of Bergen Erich Pontoppidan (1698–1764) also discussed the northern lights as being an electrical phenomenon. After reciting contemporary theories like fire from volcanic eruptions in the north or reflections of solar rays from vaporous clouds high above the North Pole, as introduced by famous philosophers at the time like the Russian scientist Leonhard Euler (1707–1783), Pontoppidan expressed himself in a very humble tone as he wrote:

> "Are somebody expecting that I should tell my opinion about this problematic matter, then it probably would not be less reasonable than what here is already referred to, if one presented the idea, that the northern light is caused by the electricity of the ether in the air" [*Pontoppidan*, 1752, 7–23].

Pontoppidan based his statement on a work by the French assistant to Isaac Newton (1642–1727), John Theophilus Desaguliers (1683–1744), who with reference to an experiment by Francis Hawksbee (Hauksbee) (1660–1713) wrote: "I suppose Particles of Air to be Electric Bodies always in state of Electricity, and that Vitreous Electricity" (vitreous electricity, that is, positive electricity). Desaguliers then described Hawksbee's experiment:

> "Having pumped out all the air from a Glass Globe, he caused it to turn its Axis very swiftly, by means of a Rope with Wheel and Pulley; then rubbing the Glass with his hand during Motion, there appeared a great deal of Light of a purple Colour" [*Desaguliers*, 1742, 140–143].

Pontoppidan compared this rotating globe with the rotating Earth, and wrote:

> "One can imagine the terrestrial globe surrounded by air like the glass-globe in an electric machine. When the air is pumped out and the globe is rotating very fast, a purple coloured flame is coming into being, the same colour as exists in the northern light, and this flame must be Ether igneous."

Further Pontoppidan wrote:

> "The northern light observed towards the Pole or the axis of the globe can not be caused by ether alone but can also be the very ether itself; which, being aggregated, gives way to the impression of the humid air, and mounts and floats above the clouds, whose motion likewise renders variable" [*Pontoppidan*, 1752, 16–17].

The Russian polyhistor Mikhail Lomonosov (1711–1765) discussed similar experiments as Hawksbee had demonstrated and he claimed:

> "During excitation of an electric force in the sphere, from which air is drawn out, sudden rays emitted, and instantly disappeared, and at the same time, new ones in their places popped up, so it looked like continuous glitter. In the northern lights flashes or beams do not suddenly occur to the extent of entire space, but behave similarly. The pillars of the northern lights shining as stripes on the surface of the electric atmosphere in subtle or in pure are very nearly perpendicular to the ether, as in the aforementioned electric sphere from a concave circular surface to the center of converging rays." [*Chernouss*, 2012, 105–107]

In 1779, the American scientist, inventor, and diplomat Dr. Benjamin Franklin (1706–1790) published an article where he assumed that the warm and moist air rising in the tropical zones contains electricity that is transported by winds to the polar regions and that equatorial return winds bring cooler air back from the poles to the tropics. He wrote:

> "May not then the great Quantity of Electricity brought into the Polar Regions by the Clouds which are condens'd there & fall in Snow, which Electricity would enter the Earth but cannot penetrate the Ice; May it not, I say, as a bottle overcharg'd, break thro' that low Atmosphere and run along in the Vacuum over the Air towards the Equator, diverging as the degrees of Longitude enlarge, strongly visible where densest, and becoming less visible as it more diverges, till it finds a Passage to the Earth in more temperate Climates; or is mingled with their upper Air?If such an Operation of Nature were really performed, would it not give all the Appearances of an Aurora Borealis?" [*Franklin*, 1779, 291–297]

Definitely, Franklin related the aurora to a global stream of electricity, what we today would call an electric current.

Franklin wrote a letter to Lomonosov where he expressed his opinion about the nature of the aurora borealis. Lomonosov commented on this letter in the following way:

> "Franklin's guess about the northern lights, which he refers to by a few words in the same letter of my theories is very different. He attracts electrical matter of the northern lights from the equatorial zone, but I find it in the same place, i.e. in the air and everywhere present. He does not define its place, but I think it is above the atmosphere, …contains my long standing view that the northern lights arise from the motion of the ether" [*Chernouss*, 2012, 105–107; *Eather*, 1980, 59].

1.2.2. Electric Currents Related to the Northern Lights

In 1820, the Danish physicist Hans Christian Ørsted (1777–1851) discovered electromagnetism, that is, that an electric current could create a magnetic field at a distance. A door was then opened to understand the geomagnetic field variations in terms of global currents.

The French physicist Auguste de la Rive (1801–1873) in 1849 wrote a letter to the French prime minister and physicist M. Arago (1786–1853) with a laudatory phrase in the following way:

> "I have only followed the route which you yourself have traced; for more than thirty years ago, you, with indefatigable perseverance, established by your numerous observations the remarkable concordance which exists between the appearance of the Aurora Borealis and the disturbance of the magnetic needle" [*De La Rive*, 1849, 40–46].

Seemingly, Arago had repeated the original work by Celsius, Hiorter, and Graham.

De la Rive had the idea that as an electric current is floating from the hot end of a rod to the cold end, there is a current floating from the warm end at the bottom of a column of air at the equator to the top, that is, a vertical upward current exists from the Earth's surface at the equator, and he wrote:

> "Thus we have a circuit formed; each annular stratum of the atmosphere gives rise to a current, which travels in the upper portion of the stratum towards the pole, re-descends towards the earth through the atmosphere around the pole."

And finally

> "the currents pass also from the equator to the pole in the upper regions of the air, and from the pole to the equator upon the surface of the earth" [*De La Rive*, 1849, 42]. This idea has certainly a lot in common with Franklin's model.

The Scottish physicist Balfour Stewart (1828–1887) in 1886 when discussing observed solar-diurnal variations in the terrestrial magnetism, had to dismiss the Earth-currents as the cause, and maintained:

> "And we are therefore driven to regard electrical currents as being the only conceivable cause, if this cause is to be located in the upper atmospheric regions. In the first place, it may be said that while undoubtedly rarified air is a conductor of electricity, yet it is not a good conductor, and where can we look for sufficient potential to drive current through these upper atmospheric regions? To this I would reply that as a matter of fact we know that there are visible electric currents in the upper atmospheric regions which occur occasionally at ordinary latitudes, and which are very frequent, if not continuous, in certain regions of the Earth. I allude to the aurora which is unquestionably an electric current, and must therefore influence the magnetic field.
>
> While we can with the greatest ease account for it by means of a system of currents in the upper regions of the Earth's atmosphere." [*Stewart*, 1886, 44]

1.3. TIDAL MOTIONS AND THE DYNAMO THEORY

The British physicist Arthur Schuster (1851–1934), who studied the variations of the vertical component of the magnetic field (the z-component), stated in 1889:

> "The horizontal movements in the atmosphere which must accompany a tidal action of the Sun or Moon or any periodic variation of the barometer such as is actually observed, would produce electric currents in the atmosphere having magnetic effects similar in character to the observed daily variation" [*Schuster*, 1907, 163–204].

Here is probably one of the first statements in history relating the daily magnetic field variations to the existence of tidal motions, and Schuster continued:

> "If we endeavor to carry the investigation a step further and enquire into the probable origin of these currents, we have at present no alternative to the theory first proposed by Balfour Stewart, that the necessary electromotive force are supplied by the permanent forces of terrestrial magnetism acting on the bodily motion of masses of conducting air which cut through its line of force" [*Schuster*, 1907, 163–204].

Here Schuster introduced for the first time the dynamo theory as an explanation of the diurnal variations of the magnetic field.

Sidney Chapman (1888–1970) later followed up on the studies of tidal motion based on a statistical analysis of magnetic variations from a global network of stations and reached the following conclusion about the *S* (solar) and *L* (lunar) components of the diurnal variations:

> "There is, in any case, little or no reason to doubt that the S and L currents flow in our atmosphere in a layer which is very nearly spherical and concentric with the Earth" [*Chapman*, 1919, 1].

This view resembles De La Rive's ideas but it leaves a system without vertical currents.

1.4. THE BIRKELAND-STØRMER CURRENT SYSTEM

In 1896, a young Norwegian physicist Kristian Birkeland (1867–1917) presented an idea where he assumed that the northern lights where caused by cathode rays streaming out from the Sun, being soaked up by the Earth's magnetic field and forced toward the poles of the globe where they created the northern lights. [*Birkeland*, 1896]. According to his theory there was no strong limitation of how far down in the atmosphere the cathode rays could reach. For Birkeland, the height of the aurora became an important issue.

In 1898, Birkeland received support from the Norwegian government to build an observatory, the Haldde Observatory, and an annex observatory, Talvik, 3.4 km apart at 900 m above sea level in northern Norway in order to study the nature of the northern lights.

Birkeland's initial objective was to measure the height of the northern lights by triangulation from the two observatories connected by a telephone line. He lost his primary goal partly due to the short baseline (3.4 km) and partly because his optical equipment had too low sensitivity. Fortunately, he brought with him magnetometers to the mountain and could combine magnetic records from his observatory with recordings at lower latitudes like Potsdam and Pavlovsk. Birkeland realized that such magnetic-field variations could not be used to derive the full current vector, but only the horizontal component or the equivalent current. From these magnetic data, however, he drew up a map (Fig. 1.1) of a cross-polar horizontal current system that resembles the convection current systems often discussed today.

Birkeland again applied to the Norwegian government for support to discharge a new expedition to the Arctic, and, in 1902–1903, he had 4 stations installed in Iceland, Spitsbergen, Novaia-Zemlja, and Bossekop, respectively. By combining magnetic records from these stations with similar recordings from 23 other stations around the world, he came to the conclusion that field-lined electron precipitation formed vertical currents that connected to a horizontal current along the auroral arcs (Fig. 1.2). He also expanded his model by including two antiparallel current sheets feeding a horizontal part along the auroral arc (Fig. 1.3).

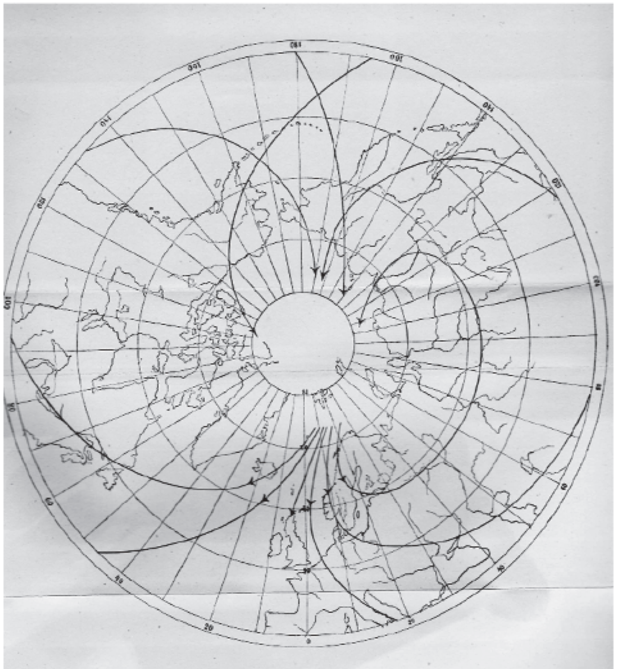

Figure 1.1 Birkeland's convection current system from 1901. The arrows represent the motion of the cathode rays. From *Birkeland* [1902].

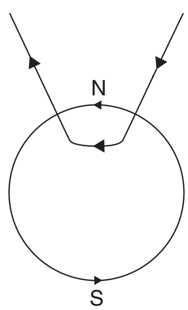

Figure 1.2 Birkeland's line-current model where vertical currents are closed by a current along the auroral arc. After *Boström* [1967].

It is surprising that, when reading Birkeland's large work entitled *The Norwegian Aurora Polaris Expedition 1902–1903, Volume I, On the Cause of Magnetic Storms and the Origin of Terrestrial Magnetism* [*Birkeland*, 1908], actually very little is found in terms of visual observations of the aurora itself. The main part of this gigantic work refers to the interpretations of worldwide magnetic records in terms of global currents. As a matter of fact, Birkeland drew most of his conclusions about the creation of the aurora from experiments in the laboratory, where the Terrella experiment was the central piece. By his small "universe," he could create the auroral rings as well as equatorial ring currents that he

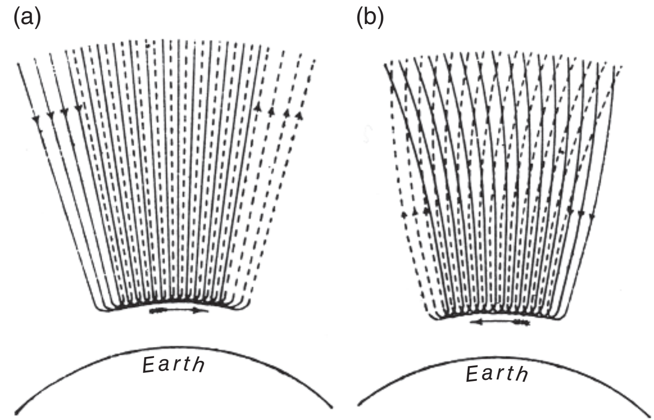

Figure 1.3 Birkeland's expanded current system including two antiparallel current sheets feeding a horizontal current along the auroral arc. The arrows indicate the direction of the motion of cathode rays. From *Birkeland* [1908].

associated with similar phenomena in the real world. Certainly, the experiment was not scaled in true proportions, but, nevertheless, the phenomena discovered gave associations to the reality.

The Norwegian mathematician Carl Størmer (1874–1957) was much inspired by Birkeland's work and set out to calculate the trajectories of electrically charged particles in a magnetic field in an attempt to explain the formation of auroral rays, and so on (Fig. 1.4). He traced the particles from the Sun toward the Earth and found that they often reached the atmosphere at higher latitudes than the 23 degrees from the pole where the auroras most often occurred. In order to improve the agreement, he weakened the magnetic field in his calculations by introducing an eastward (westerly) current around the globe in the equatorial plane at a distance from the Earth. This was probably the first indication of the equatorial ring current ever proposed [*Størmer*, 1955].

1.5. CURRENT SYSTEMS FOR MAGNETIC STORMS

The report from Birkeland's second expedition to the Arctic had, as stated above, a subtitle: "On the cause of magnetic storms and the origin of terrestrial magnetism" [*Birkeland*, 1908].

Birkeland attributed the equatorial storms to flow of electrons at great distances from the Earth: the positive storms were due to electrons deflected away from the Earth, westward, on the sunward side, and the negative storms were due to electrons deflected eastward round the back of the Earth.

Schuster criticized this idea on the grounds that a beam of electrons from the Sun could not hold together against their mutual repulsion, in sufficient strength to provide

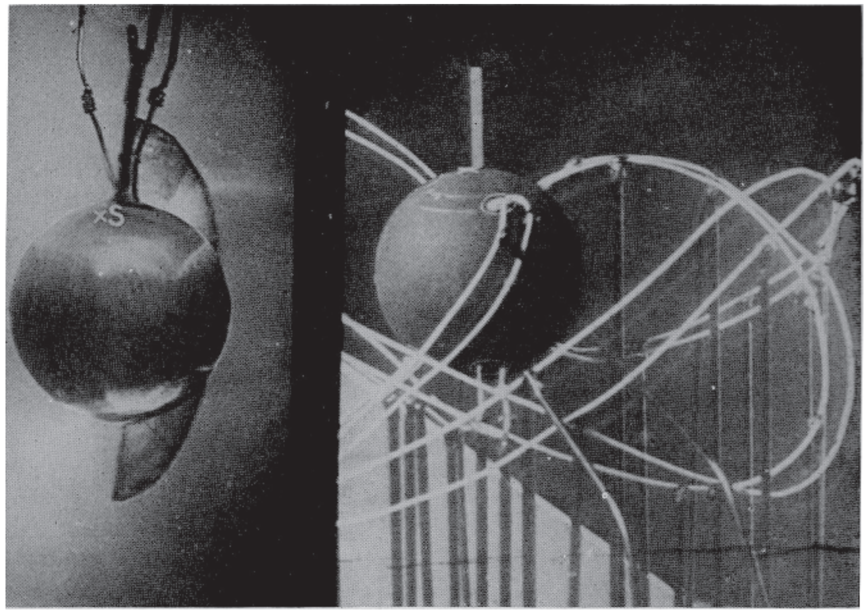

Figure 1.4 A comparison between Birkeland's artificial aurora from the Terrella experiment (left) and Størmer's particle trajectories illustrated by spiral models (right). From *Birkeland* [1908].

the electric currents near the Earth as proposed by Birkeland, and he stated:

> "We must conclude that a swarm of electrons packed with sufficient density to cause a magnetic effect would soon get dissipated laterally into space until its magnetic action becomes negligible."

He continued:

> "The results of the previous investigation conclusively prove that magnetic storms cannot be due to a direct magnetic action of swarms of electrified particles" [*Schuster*, 1911, 44–50].

In 1918, Chapman, however, in contrast to Schuster, supported the idea of precipitating electric particles with the same type of electric charge in order to explain the vertical atmospheric motions that he believed to have observed in connection to a magnetic storm. He wrote:

> "A magnetic storm is generated by the entry into the earth's atmosphere of numbers of electric particles, mainly or entirely of the same sign of charge. They penetrate to a more or less definite level in the upper atmosphere, this level depending on the density and composition of the atmosphere, and upon the physical nature and velocity of the particles."

He continued:

> "On the theory to be described, this cause is a system of electric currents which flow, in more or less horizontal strata, in the upper atmosphere" [*Chapman*, 1918, 78].

He further divided the current system into two subsystems, a latitudinal and a meridional one (Fig. 1.5):

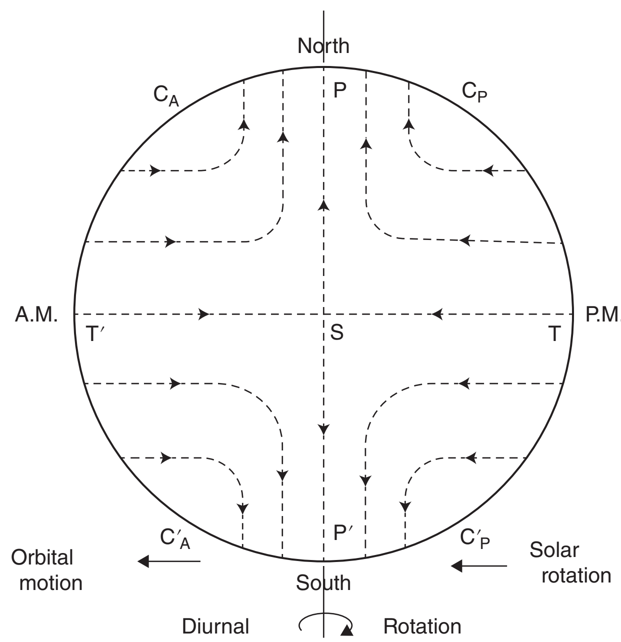

Figure 1.5 Chapman's model of the local storm variation current system that has a certain symmetry about the radius vector from the Sun and is divided into four similar and self-contained quadrantal parts by the "solar meridian." From *Chapman* [1918].

> "The first current system, in which the circulation is round parallels of latitude, is symmetrical about the earth's axis. The electromotive force (E.M.F.) impelling the current arises from inductive action occurring in the plane normal to the E. M. F., i.e., in the meridian plane at each point. The most general action in this plane can be resolved into component parts, in one of which a vertical motion of the atmosphere takes place across the horizontal component of the earth's magnetic field, while in the other a horizontal current of air crosses the vertical magnetic field." [*Chapman*, 1918, 76]

Finally, based on the background of the work by the Norwegian scientists Störmer, Vegard, and Krogness (L. Vegard [1880–1963] and O. A. Krogness [1886–1934] were both students of K. Birkeland), Chapman associated the occurrence of the aurora with these penetrating particles:

> "Auroræ may themselves be the visible manifestation of vertical electric discharges of unusual intensity. Precipitation would seem to be ordinarily confined to high latitudes, extending during a storm over a much wider area, but the injection may not be confined to the regions where auroræ are actually visible" [*Chapman*, 1918, 80].

In 1919, F. A. Lindemann criticized Chapman's theory with the following strategy:

> "The best way to approach the subject is probably by criticising the theory now probably most generally accepted, which has been most elaborately worked out by Dr. Chapman. The recognition of the fact that a radial current on the earth would explain the magnetic phenomena is undoubtedly a most valuable advance, and with this part of his theory it is not proposed to tamper."

And Lindemann continued:

> "Dr. Chapman assumes that beams of α rays are emitted by parts of the solar surface and that the earth is subjected to a magnetic storm when it passes through a beam of this sort" [*Lindemann*, 1919, 669].

The strongest arguments Lindemann put forward against Chapman's theory were the following:

> "There are a number of reasons which show that α rays alone cannot be the true cause of magnetic storms, the main ones being that they cannot be produced on the sun in sufficient quantities, that they cannot proceed as a beam for one or two solar diameters on account of the mutual repulsion on the particles, and finally that they could not approach the earth after the first few seconds on account of the charge the earth would rapidly acquire…. The hypothesis to be examined therefore is that an approximately equal number of positive and negative ions are projected from the sun in something of the form of a cloud and that these are the cause of magnetic storms and auroræ." [*Lindemann*, 1919 673]

Here Lindemann for the first time touched upon what we today call the "Solar Wind."

Lindemann argued against an electromotive force in the solar atmosphere and believed the particles in the cloud were driven out from the Sun by the radiation pressure.

> "It appears certain therefore that such clouds of ionized gas can exist, and that they would be projected radially from the sun at such a speed that they would naturally spread out enough by the time they reached the earth to account for the observed duration of magnetic storms" [*Lindemann*, 1919, 679].

As the ions were heavier than the electrons, the radiation pressure would more effectively drive ions and the electrons would lag behind with the consequences that a radial electric field would be created.

Chapman accepted the criticism by Lindeman and wrote in the 1930s, together with C. V. A. Ferraro, a string of papers related to *A New Theory of Magnetic Storms* [*Chapman and Ferraro*, 1930, 129–130].

> "We have not examined closely the extent to which the stream will cause inflow of ions and electrons into the earth's atmosphere in the polar regions, or how this inflow will give rise to the observed currents along auroral zones; but it seems likely that present theories of the auroræ will need to be modified, because the particles of a neutral stream can approach much closer to the earth, in the equatorial plane, than the single charged particles hitherto considered."

Concerning the currents responsible for the magnetic deviation during a magnetic storm they stated:

> "In the second phase of a magnetic storm the earth's horizontal force is decreased. We attribute this to the formation of a westerly current around the earth, due primarily to the flow of charges across the space "behind" the earth (viewed from the sun)" [*Chapman and Ferraro*, 1930, 129].

Included, in their paper was Figure 1.6, which shows the charged layers along BB' (positive) and CC'(negative) situated in the equatorial plane behind the Earth as seen from the Sun, and being due to the polarization of the stream by the magnetic field. An electric field would be set up to bring the charges between the layers that would enforce the ions from moving from BB' to CC', but the magnetic field would preclude the electrons from moving in the reverse direction. Electrons would instead flow downward and upward along the magnetic lines of force to neutralize the positive ions that traverse from BB' to CC'. From this they maintained that a westerly current could be set up around the Earth, the equatorial ring-current.

Ferraro made a critical survey of their common work until 1933 and stated,

> "We have not been able to make any serious attempt at a mathematical discussion of the processes involved in the main phase of the storm, which we think is due to a westerly current flowing round the Earth at a distance of several Earth radii" [*Ferraro*, 1933, 259].

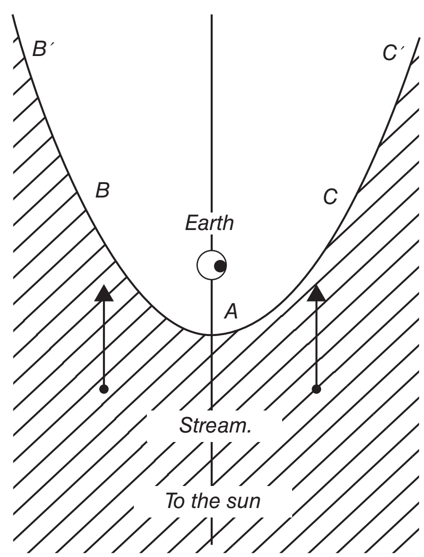

Figure 1.6 A figure presented by *Chapman and Ferraro* [1930] to explain the separation of positive charges along BB′ and negative charges along CC′ in the particle stream behind the Earth seen from the Sun.

Summing up their common work in contrast to Birkeland and Störmer's idea, Ferraro wrote:

> "Our theory differs in many respects from previous corpuscular theories (associated especially with the names of Birkeland and Störmer), especially in that we supposed the solar streams to be neutral but ionized (as had been suggested by F. A. Lindemann) and to approach much nearer to the Earth in the equatorial plane than electric corpuscles considered by Birkeland and Störmer" [*Ferraro*, 1933, 253].

Chapman in 1935 [*Chapman*, 1935] continued on the work on the current system related to magnetic storms and published a model of the complete current system about 16 hours after the outbreak of a magnetic storm. The currents were given as calculated on the assumption that there was no current supply to the zones from the outside.

During the 1960s, global magnetic recordings from the International Geophysical Year (IGY) 1957–1958 were extensively used to infer equivalent currents. Since vertical currents cannot be derived from ground-based geomagnetic recordings only, the equivalent current is a pseudo current in the horizontal plane. *Matsushita* [1967] derived the so-called averaged mean S_q current system for different periods of the day (Fig. 1.7).

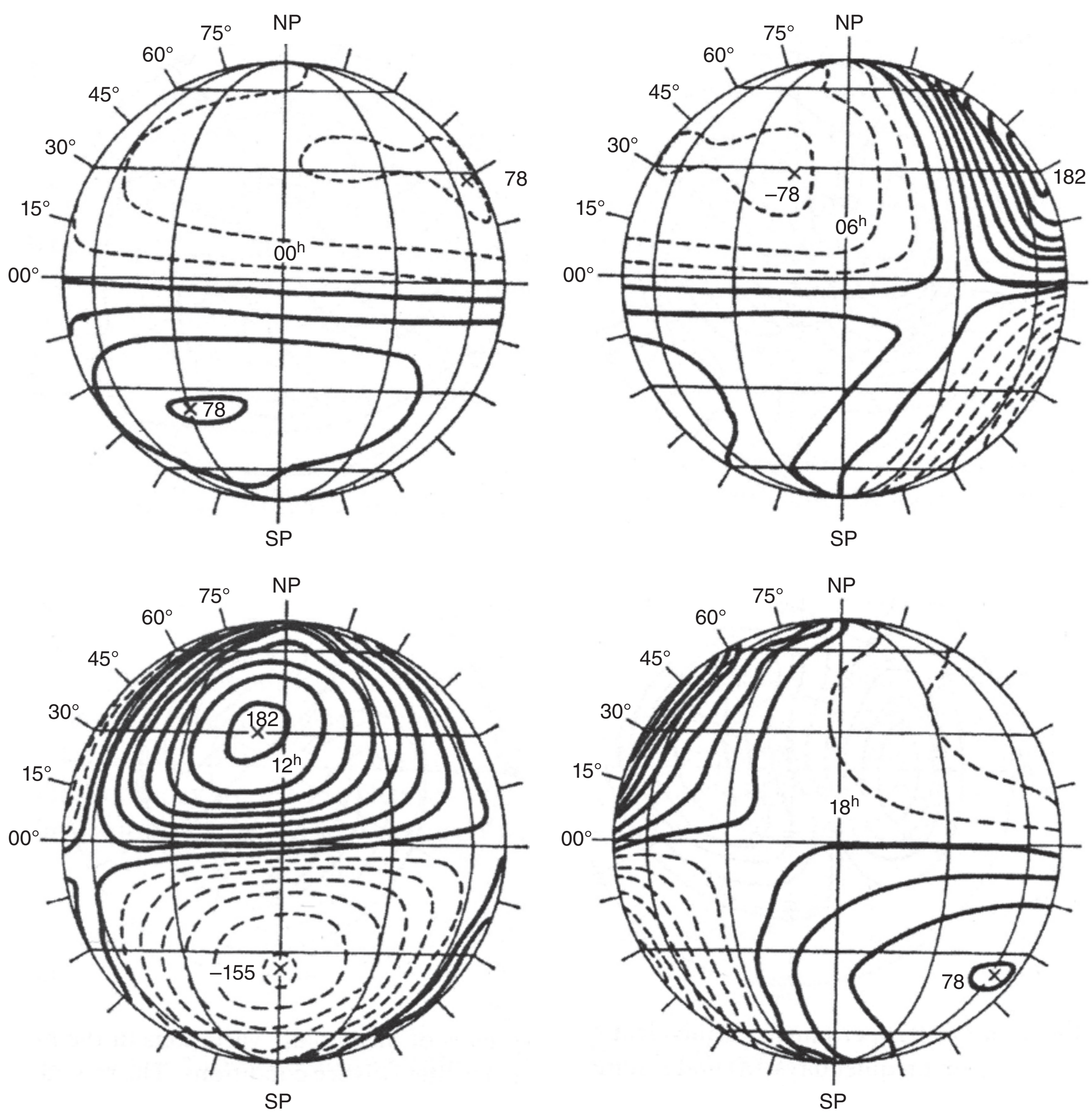

Figure 1.7 Average mean S_q (solar quiet) current systems during the IGY (International Geophysical Year) viewed from the magnetic equator at 00:00, 06:00, 12:00, and 18:00 meridian. The numbers near the crosses indicate vortex current intensity in units of 10^3 A. The distance between the current lines corresponds to 2.5 10^3 A. From *Matsushita* [1967].

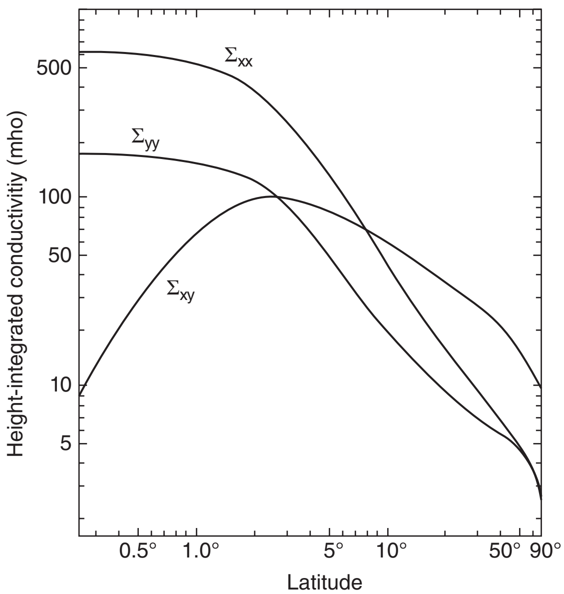

Figure 1.8 Model calculations of the height-integrated conductivities as function of magnetic latitudes derived by *Fejer* [1964].

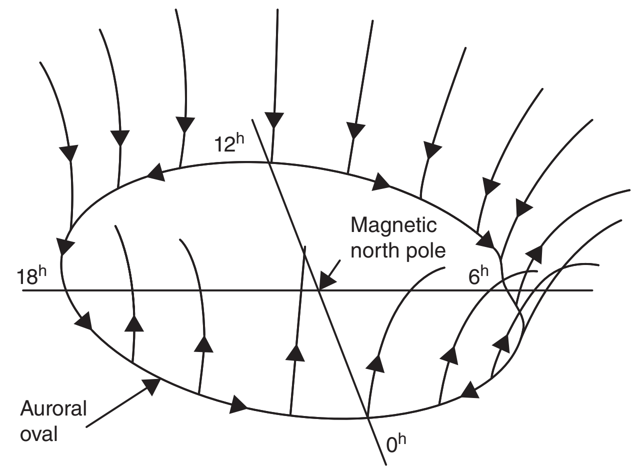

Figure 1.9 The high latitude part of Alfvén's current system showing connection between the auroral zone and field-aligned currents, with a downward current on the dayside and an upward current on the nightside, linked to an eastward current in the evening side and a westward current in the morning side along the auroral oval. From *Alfvén* [1940].

Such data were also widely used to derive electric fields and neutral winds in the upper atmosphere when world-wide models for the ionospheric conductivities were introduced. *Fejer* [1964] calculated such models (Fig. 1.8) that played an important role as input to many of the analyses of the global variations in terms of *F*-region neutral winds and electric fields.

1.6. HANNES ALFVÉN INTRODUCED PLASMA PHYSICS TO MAGNETOSPHERIC RESEARCH

In 1939 the Swedish physicist Hannes Alfvén (1908–1969) published a theory about magnetic storms and the aurora where he criticized the assumption by Chapman and Ferraro that the magnetic field inside the beam is zero [*Alfvén*, 1939]. Later on he offered them an excuse:

> "The assumption that the magnetic field inside the beam is zero was natural at the time when Chapman and Ferraro made it" [*Alfvén*, 1955, 50–64].

Alfvén maintained that the beam possessed a magnetic field that was "frozen in" into the highly conducting matter, and due to the motion of the beam, this magnetic field produced an electric field. He stated, "that, an ionized, but on the average neutral, stream emitted from the sun must be electrically polarized due to its motion in the solar magnetic field. In fact any conductor–and the stream is certainly a good conductor–moving with the velocity v in a magnetic field H becomes polarized so that it posses an electric field E = v/c H. The direction of the field is perpendicular to the magnetic field as well as to the velocity" [*Alfvén*, 1939]. Alfvén introduced a forbidden region in space outside the Earth and argued:

> "Up to the borderline of the forbidden region the ions and electrons neutralize each other so that the resultant space charge is small. On the day side of the borderline the positive ions are no longer neutralized by the electrons. Hence a positive space charge is built up. On the other hand, on the night side near the borderline the electrons are not neutralized by the positive ions. This means that a negative space charge is produced. The positive space charge on the day side and the negative space charge on the night side of the borderline may neutralize each other through a discharge along the magnetic line of force. Charge is transported from the equatorial plane along the magnetic lines of force to the upper atmosphere, which is hit along one curve around each pole, which is the projection along the lines of force of the borderline upon the earth's surface. This curve, over which the discharge takes place, marks the region where the aurora occurs." [*Alfvén*, 1939, ch. 6]

An eastward current in the equatorial plane was also introduced all around the globe, the equatorial ring current, as Störmer proposed more than 20 years before. Field-line transport of electric charges was again connected to the creation of aurora as Birkeland did about 40 years earlier.

Later, Alfvén improved his model and an eastward current was introduced on the evening side along the auroral oval and a westward current on the morning side (Fig. 1.9). Alfvén's work marked a change of paradigm and introduced plasma physics to the understanding of magnetospheric processes.

1.7. INTO THE SPACE AGE

In 1973, *McPherron et al.* [1973] carried out an extensive study of the cause of auroral substorms where they combined ground and geosynchronous magnetic field observations, and introduced a current system including the so-called current wedge (Fig. 1.10) [*McPherron et al.,* 1973]. Like Alfvén, their current system included field-aligned currents between the nightside equatorial plane and the polar latitudes feeding the auroral electrojet. No currents, however, were drawn on the dayside.

Alfvén inspired young scientists in Sweden to engage themselves in studies of magnetospheric physics. One of them was Rolf Boström, who in 1964 wrote a paper about the polar substorm current system where he drew up two models for the currents [*Boström*, 1964]. One was based on the idea of a line current as introduced by Birkeland but with currents flowing along magnetic field lines in contrast to vertically, as Birkeland proposed. In the ionosphere, the current formed the auroral electrojet probably confined to the visible auroral structure. Boström specified the ionospheric current in more details than previously discussed, and wrote:

> "However, since the Hall current must be continues across the boundary of the electrojet a southward polarization electric field will be produced which lowers the northward current component in the electrojet. It will also drive a westward Hall current in the region of enhanced conductivity, the net effect is an intense confined electrojet" [*Boström*, 1967].

In his second model (Fig. 1.11), Boström assumed that plasma motions in the magnetosphere drove the current system and that Pedersen currents in the ionosphere were linked to sheet currents flowing from the northern and southern edges of the electrojet that is represented by the Hall current. This was actually a further development of Birkeland's original sheet current model. According to Boström, the Pedersen current in the ionosphere represents an energy-loss mechanism since its flow is along the electric field. The corresponding current that flows transverse to the sheet currents in the magnetosphere brakes the plasma motions there, and represents the dynamo, the driving mechanism for the current system [*Boström*, 1964].

In 1970, Armstrong and Zmuda, based on satellite measurements of transverse magnetic disturbances in the auroral oval, presented a field-aligned current system that was "found to fit qualitatively a two-sheet current model proposed by R. Boström. Currents flow into the ionosphere along the higher-latitude sheet and out along the lower-latitude sheet" (7122–7127). An equatorward Pedersen current linked to a downward current from the magnetosphere formed by precipitating positive particles and thermal electrons streaming out of the ionosphere [*Armstrong and Zmuda*, 1970].

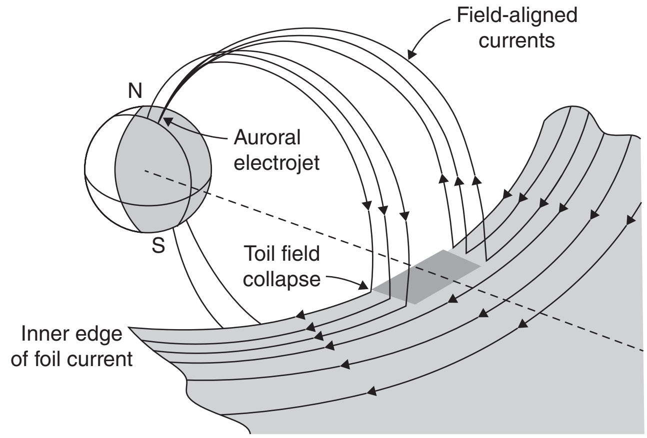

Figure 1.10 The current wedge as introduced by *McPherron et al.* [1973].

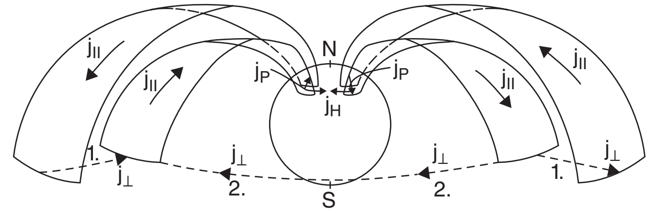

Figure 1.11 The second current system proposed by Boström including the Hall and Pedersen currents in the ionosphere. From *Boström* [1964].

Park and Cloutier [1971, 7714–7733] derived from a rocket-borne experiment at Fort Churchill, Canada, a current system adjacent to a quiet auroral arc. Magnetic field variations were measured by a vector magnetometer in vicinity to the arc. "The data were interpreted in terms of a model current system consisting of a northwestward electrojet and two oppositely directed Birkeland's sheet currents, all lying in planes approximately parallel to the auroral arc." A westward electrojet was situated at the position of the arc connected to an upward field-aligned current due to precipitating electrons of 2 to 18 kev. The two field-aligned currents were linked by a Pedersen current in the northward direction driven by a northward field in opposition to the model by Armstrong and Zmuda. According to the authors: "The over–all current configuration differs from theoretical models proposed by Boström and Atkinson." The main reason for this discrepancy was probably the orientation of the arc. Boström's model predicted an eastward current, while the rocket experiment occurred in a westward electrojet. Furthermore, in Boström's model the sheet currents flowed at the edges of the arc where there were horizontal gradients in the conductivity, rather than within the arc, and the electrojet was located between the current sheets. Boström's model also predicted an electric field perpendicular to the arc while the rocket experiment indicated that the field could not be perpendicular to the arc and the electrojet might have been a combination of a Pedersen and a Hall component in contrast to Boström's that indicated that the electrojet was driven by a Hall current only.

1.8. THE RELATION OF THE IONOSPHERIC CONDUCTIVITIES TO THE CURRENTS

So far in the search for a global current system with special emphasis on the auroral region, individual in situ measurements had been performed by rockets to carry out what were basically case studies, and little was known with respect to the time-dependent interplay between electric fields and ionospheric conductivities in forming the details of the currents. When an incoherent scatter radar was introduced to the auroral region in Chatanika, Alaska, in 1971, a new area was opened for ionospheric research at high latitudes. Here *Brekke et al.* [1974], for the first time were able to make long time series measurements of the time development of the electric field and neutral wind components as well as the height-integrated Hall and Pedersen conductivities during auroral substorms. These results (Fig. 1.12) showed that the electric field was strongly polarized, being northward in the evening and southward in the morning. The conductances, however, were most strongly enhanced during southward fields in the morning hours, and the neutral wind played a relative weak role compared with the electric field.

On 13–14 March 1972, the radar observed a very special event (Fig. 1.13). The southward E-field (E_x) was strongly enhanced with respect to the westward field (E_y) with a factor of $E_x / E_y = 3$ at the same time as the Hall conductance Σ_H was enhanced by a factor of 3 with respect to the Pedersen conductance Σ_P. As it turned out that the northward electric current corresponding to fluctuations in the magnetic D-component was close to zero, the event very closely matched the Boström model of the polarization current in an auroral arc. The strength of the westward auroral electrojet was given by $J_y = \Sigma_P (1 + (\Sigma_H/\Sigma_P)^2)E_y \approx 10\Sigma_P E_y$, and the polarization factor was close to 10.

Iijima and Potemra [1976] presented a summary of the distribution and flow directions of large-scale field-aligned currents determined from observations of field-aligned currents at 800 km altitude in the high-latitude region by the satellite Triad (Fig. 1.14).

The currents on the equatorward side are the so-called Region 2 currents, which are into the ionosphere in the evening and out of the ionosphere in the morning. The currents on the poleward side are the so-called Region 1 currents, which are into the ionosphere in the morning and out of the ionosphere in the evening.

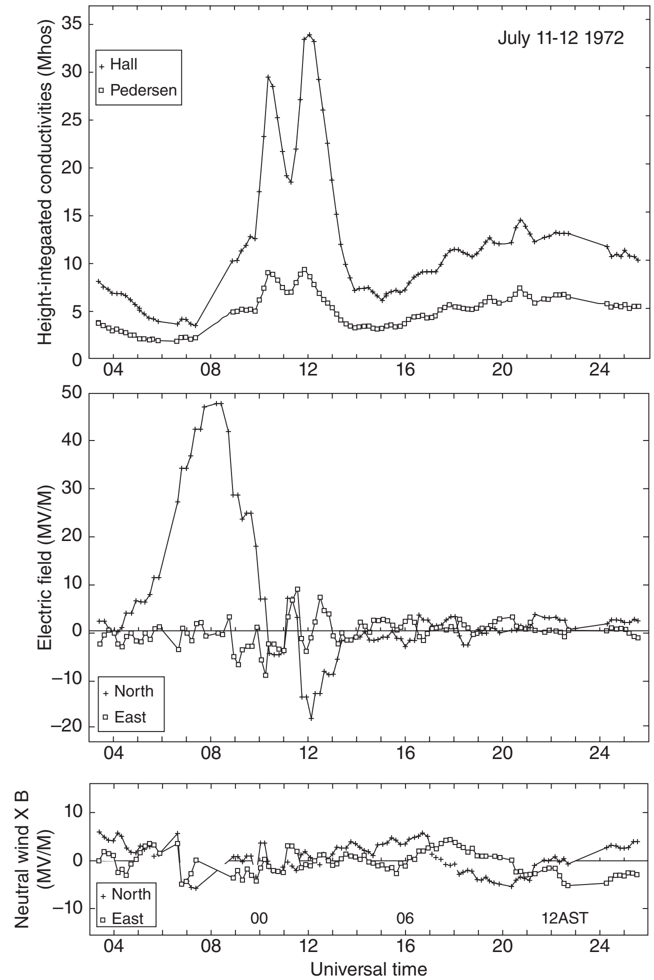

Figure 1.12 (Top) Height-integrated Hall and Pedersen conductivities; (middle) horizontal electric field components; (bottom) horizontal neutral wind components (u x B). All derived in the auroral zone by the incoherent scatter radar Chatanika, Alaska, 11–12 July 1972. From *Brekke et al.*. [1974].

By combining the observations obtained from Triad with the measurements done by Chatanika radar and later confirmed by the EISCAT (The European Incoherent Scatter Association) incoherent scatter radar in Scandinavia (Fig. 1.15), a current system prevails that is much in agreement with the second model by Boström. On evening side, a downward field-aligned current is flowing into the ionosphere on the equatorward side and an upward current on the poleward side of the auroral oval. A Pedersen current aligned with the northward E-field links these currents. On the morning side, the direction of the currents and the electric field are reversed. The ionosphere is therefore a load to the system. In the equatorial plane, however, the currents are directed against the electric field of the magnetotail. The current

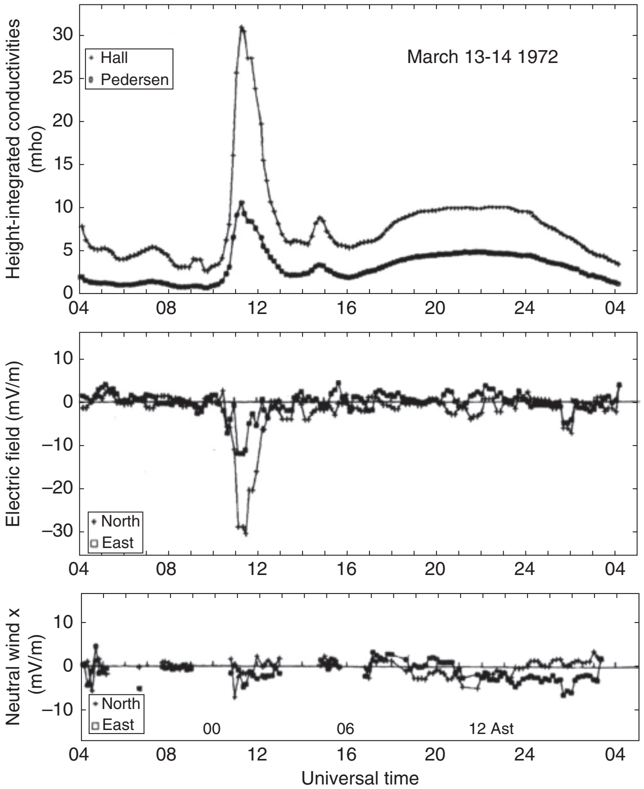

Figure 1.13 (Top) Height-integrated Hall and Pedersen conductivities and (bottom) the horizontal electric field components in the west and southward directions derived by the Chatanika radar on 13–14 March 1972. From *Brekke et al.* [1974].

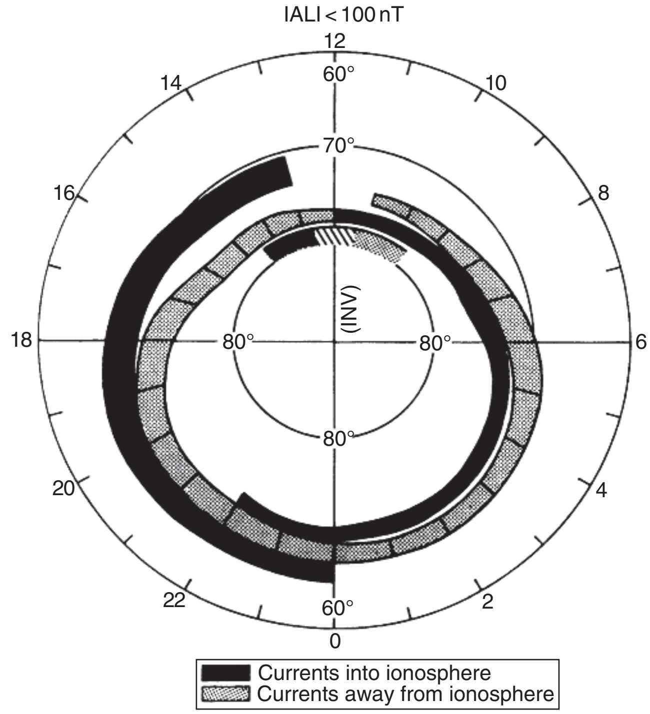

Figure 1.14 Schematic model of observed field-aligned currents as deduced from satellite observations by *Iijima and Potemra* [1976].

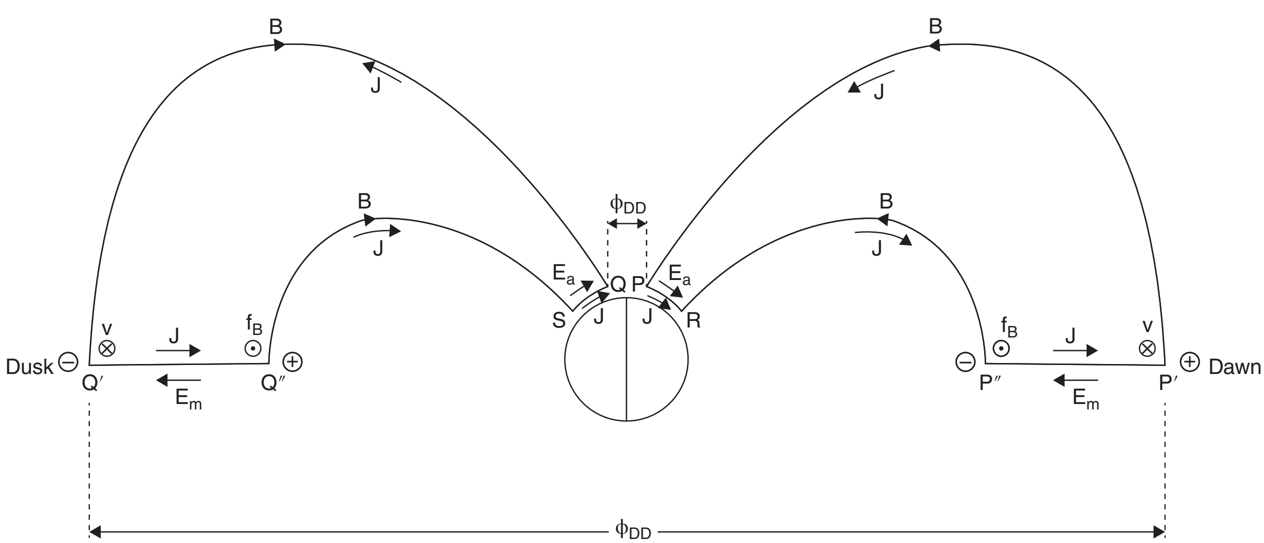

Figure 1.15 A synthesis of the satellite observations of field-aligned currents by the Triad satellite and ground-based observations of electric fields and conductances by the Chatanika and EISCAT incoherent scatter radars showing the current system between the nightside magnetosphere and the auroral zone. From *Brekke* [2013].

force $f_B = j \times B$ is therefore set up as a brake against the magnetospheric convection v.

1.9. CONCLUSION

This review shows that the progress of our understanding of the electric currents in geospace has gone through a progressive development from the time of the Enlightenment in the early eighteenth century to the Space Age in the 1970s. Important steps were made in the late part of the nineteenth century when magnetic field variations were found to be caused by electric currents in the upper atmosphere. The aurora borealis was believed to be an electric phenomenon by several authors as early as the 1750s. The current system linking the creation of the aurora became a main field of interest in the beginning of the twentieth century and has remained so until our time.

At present, we have a large diversity of instruments and methods such as satellite and ground-based experiments of different kinds and capacities as well as dedicated computer models to study these current systems further. What appears to be lacking, however, is a more detailed knowledge of the variations of the interplay between the ionospheric conductivities, electric fields, and neutral winds in space and time, that is, the three most important factors in determining the ionospheric currents. So far, observations of these parameters are available partly integrated over large areas and extended time periods, but that does not satisfy studies of detailed variations of the plasma processes taking place in the upper atmosphere during magnetospheric storms and auroral displays.

The plan to install a phased array incoherent scatter radar system EISCAT_3D in Scandinavia, with unprecedented spatial and time resolutions, is anticipated to lead the science of currents in geospace into a new era.

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