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Danish auroral science history

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Abstract. Danish auroral science history begins with the early auroral observations made by the Danish astronomer Tycho Brahe during the years from 1582 to 1601 preceding the Maunder minimum in solar activity. Included are also the brilliant observations made by another astronomer, Ole Rømer, from Copenhagen in 1707, as well as the early auroral observations made from Greenland by missionaries during the 18th and 19th centuries. The relations between auroras and geomagnetic variations were analysed by H. C. Ørsted, who also played a vital role in the development of Danish meteorology that came to include comprehensive auroral observations from Denmark, Iceland and Greenland as well as auroral and geomagnetic research. The very important auroral investigations made by Sophus Tromholt are outlined. His analysis from 1880 of auroral observations from Greenland prepared for the significant contributions from the Danish Meteorological Institute, DMI, (founded in 1872) to the first International Polar Year 1882/83, where an expedition headed by Adam Paulsen was sent to Greenland to conduct auroral and geomagnetic observations. Paulsen's analyses of the collected data gave many important results but also raised many new questions that gave rise to auroral expeditions to Iceland in 1899 to 1900 and to Finland in 1900 to 1901. Among the results from these expeditions were 26 unique paintings of the auroras made by the artist painter, Harald Moltke. The expedition to Finland was headed by Dan la Cour, who later as director of the DMI came to be in charge of the comprehensive international geomagnetic and auroral observations made during the Second International Polar Year in 1932/33. Finally, the article describes the important investigations made by Knud Lassen during, among others, the International Geophysical Year 1957/58 and during the International Quiet Sun Year (IQSY) in 1964/65. With his leadership the auroral and geomagnetic research at DMI reached a high international level that came to be the background for the first Danish satellite, Ørsted, successfully launched in 1999 and still in operation.

1 Introduction

Over the auroral history interval from 1582 to present included in the paper, the extent of the Kingdom of Denmark has changed considerably. Hence it is not a simple task to define precisely, which part of the international auroral science history to classify as Danish. At the beginning of the epoch, the Kingdom in addition to present Danish mainland included Norway, Iceland, the Faeroe Islands, Greenland, southern Sweden, and northern Germany (Schleswig-Holsten) in different associations with Denmark. Norway, Iceland and the Faroe Islands were in union with Denmark but had local governments. Greenland was a Colony governed from Copenhagen. Schleswig was a Danish Duchy and Holsten a German Duchy under the Danish King.

By the peace treaties following a series of unfortunate wars, the Danish Kingdom surrendered southern Sweden and a major part of Norway to Sweden in 1659–1660; the union with Norway was dissolved in 1814; Schleswig-Holsten was surrendered to Germany in 1864 (the northern part of Schleswig returned to Denmark in 1920). Furthermore, Iceland became a sovereign state in 1918 and a fully independent nation in 1943. Greenland was given home-rule in 1979 and almost full independence in 2009. The Faeroe Islands gained home-rule in 1948.

In the article the Danish auroral science history includes scientists born, raised and educated within the contemporary Danish Kingdom with emphasis on the investigations conducted at or for Danish Institutes, in particular, Copenhagen University and the Danish Meteorological Institute. In the mentioning of foreign scientists their nationalities shall be noted.

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2 The first Danish scientific observations and analyses of auroras

The first scientific recordings of auroras in Denmark were made by the astronomer (Fig. 1) Tycho (or Tyge) Brahe (1546–1601) from his observatory "Uranienborg" (Fig. 2) at the small island, Hven, situated in the belt between Denmark and Sweden a little north of Copenhagen. Tycho Brahe made numerous precise observations of stars, planets and comets but he also noted the occurrences of auroras. During the years from 1582 to 1592 he and his staff observed nearly hundred occurrences of auroras (Brahe, notes), which were later recovered by P. la Cour (1846–1908) and published in "Meteorologiske Journalen" (la Cour, 1876). However, during the last decade of his observations from 1593 until his unfortunate death after a dinner with his noble friends in Prag in October 1601, he only observed a few occurrences of auroras in Denmark, possibly due to the declining sunspot activity which came to remain low for almost a century during the so-called "Maunder Sunspot minimum" named after the English scientist E. W. Maunder (1851–1928).

The steep rise in sunspot activity in the beginning of the 18th century marked the end of the Maunder sunspot minimum during which magnetic storms and auroras were rare occurrences in Denmark. Then, as a number of large geomagnetic storms occurred in 1705–1707 during the first large sunspot maximum following the Maunder minimum, the accompanying auroras were observed and given a considerable amount of attention not only in Scandinavia but also as far south in Europe as Paris in France and the Österreich-Ungarisches (Austrian-Hungarian) Empire.

One example was the large geomagnetic storm occurring in the beginning of February 1707 (Gregorian calendar) where magnificent auroras were observed in Copenhagen. These auroras were observed by the Danish astronomer Ole Rømer (1644–1710) from Copenhagen Observatory located at the top of "Rundetårn" in the middle of the city. Ole Rømer is famous for having derived the finite velocity of light from the delay across the Earth's orbit around the Sun in the appearance of the moon orbiting Jupiter. He was deeply fascinated by the auroras and had drawings made of the displays (Fig. 3, probably after his verbal description) to illustrate an epistle: "Descriptio – Luminis Borealis quod Nocte inter 1 & 2 Febr. 1707 Hafnia visum est" to be published (Roemer, 1710) in the highly reputed book on scientific progress: "Miscellanea Berolinensia ad incrementum scientiarum". In my translation to English from the German transcript "Oluf Röemer: Beschreibung eines Nordlichtes das in Koppenhagen in der Nacht zwischen den 1ten und 2ten Febr. 1707 gesehen wurde.“ (Roemer, 1781) his description of the auroras reads:

"The beginning of the vision was at 11 o'clock. The arcs spanned from the west-north-west to the north-north-east; the largest distance from the horizon, the height, amounted to 3 degrees or 6 solar cross sections. Hereafter the phenomenon rose to a greater height and grew still brighter over its entire length; the brilliance was stronger as the Moon was hidden behind a cloud. At half past eleven another bright arc appeared over the previous one; both arcs were still without rays. At one o'clock several bright rays shot up from first the upper arc and soon after also from the lower arc. This shooting-up of rays lasted for some time during which the rays varied in different ways and with high speed. The majority rose to heights in straight lines, a few were deflected to the one or the other side. When they were about to disappear, they grew shorter and wider; their greatest height above the

Figure 1. Tycho Brahe (1546–1601).

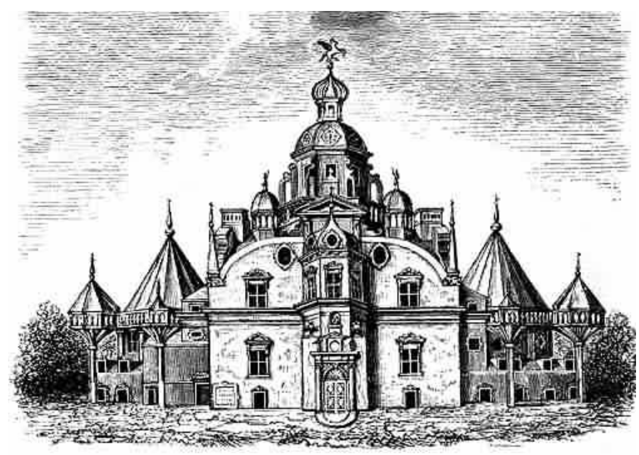

Figure 2. Tycho Brahe's astronomical Observatory at Hven: Uranienborg (from J. Ottosen, Nordens Historie, 1902).

upper arc amounted to 4 degrees. At half past two bright rays were seen everywhere and the air-vision had its greatest perfection. At two o'clock it was most intense and expanded by and large over the entire sky. At last, a dense streaky cloud covered the sky and the vision disappeared. In the recent years similar visions have been seen from the observatory between evening and morning; however, the vision has never been observed as bright and so perfect as this time."

[*"Der Anfang den Erscheinung war um 11 Uhr, und der Bogen erstreckte sich von West Nord West gegen Nord Nord Ost. Seine größte Entfernung vom Horizonte oder Höhe betrug drei Grad oder 6 Sonnendurchmesser. Hieraus stieg das Phänomen höher, und wurde oben seiner ganzen Länge nach immer mehr erleuchtet, und diese Erleuchtung war stärker, als wenn der Mond sich hinter einer Wolke zu verbergen pflegt. Um halb zwölf Uhr erzeugte sich über dem vorigen noch ein neuer erleuchteter Bogen, doch waren beide noch ohne Strahlen. Um ein Uhr schossen zuerst von dem obern Bogen, und nicht lange nachher auch von dem untern einige helle Strahlen in die Höhe. Dieses Strahlenschiessen dauert einige Zeit, allein die Strahlen veränderten sich verschiedentlich und mit großer Geschwindigkeit. Die meisten stiegen nach einer geraden Linie in die Höhe, einige neigten sich auf diese, einige auf die andere Seite. Wenn sie eben verschwinden wollen, wurden sie kurzer und breiter, und ihre grösseste Höhe über dem obern Bogen betrug 4 Grad. Um halb drei Uhr konnte man an allen Orten helle Strahlen sehen, und die Lufterscheinung hatte die grösseste Vollkommenheit. Um zwei Uhr stand es am höchsten, und verbreitete sich nach und nach über den ganzen Himmel. Endlich verhüllte ein dichter reifartiger Nebel den Himmel, und die Erscheinung verschwand. In den letzern Jahren hat man auf dem Observatorium eine ähnliche Erscheinung beobachtet, und zwar allemal in der Gegend zwischen Abend und Morgen, allein niemals hat man dieses Phänomen so erleuchtet und so vollkommen gesehen, als diesesmal."*]

This is the first Danish published scientific (and quite precise) description of auroras and an auroral substorm (auroral break-up). Ole Rømer continues in this epistle to outline similar observations made on 1 March from 10 p.m. to 1 a.m. The auroral display observed in that event is illustrated in Fig. 15 of the book. Further, he describes the event occurring on 6 March 1707, which is the day before he starts to write this epistle. Ole Rømer concludes his epistle (Rømer, 1710b) with the following scientific considerations where he rejects the common beliefs on the cause of auroras being associated with extreme warm or cold weather:

"Such air-visions are seen almost every year in Norway and Iceland. The just described phenomenon must be very low and close to us; otherwise, it would have been seen much more clear and large from Pilenburg two miles (~14 km) from Copenhagen where it should, in addition, have been more vertical. It demonstrates the present rather than the future characteristics of the air, hence it does not indicate, as some people believe, warmer weather during summer and colder during winter." [*"Fast alle Jahre siehet man solche Lufterscheinungen in Norwegen und Island. Das jetzt beschriebene Phänomen mußte sehr niedrich, und uns nahe sein, denn man hat es zu Pilenburg, zwo Meilen von Koppenhagen, viel deutlicher und größer gesehen, und es mußte daher daselbst mehr vertikal sein. Es zeigt mehr die gegenwärtige als zukünftige Beschaffenheit der Luft an, denn es folgt nicht allemal, wie einige glauben, im Sommer heiteres Wetter, im Winter Kalte auf dasselbe."*]

The Norwegian vicar Jonas Ramus (1649–1718) also reports on the large auroras seen over Copenhagen in 1707 in his book, "Norrigets Beskrivelse", from 1715 (Ramus, 1715). His description resembles that given by Ole Rømer and he dwells on the assumption that auroras were related to gaseous vapours escaping from hot sources located in the polar regions. An extract of this book and also reproductions of Rømer's drawings are available in the review work by professor Joachim Friderich Ramus (1686–1769) on the history and physics of auroras (Ramus, 1745, 1747).

In spite of Rømer's rejection of the idea of auroras being caused by extreme temperatures, elements of this theory were brought forward, among others, by the Norwegian Johan Heitman (1664–1740) in his book (Heitman, 1741). Heitman considered the auroras to be the result of hefty motions in nitrogen or sulphur vapours at great heights in the polar atmosphere and he associated the variability in the occurrences of auroras to the varying temperature levels. Another philosophical treatise based on earlier descriptions of the aurora was published in 1760 by the Norwegian philosopher G. Schøning (Schøning, 1760).

Vikings from Norway and Iceland have inhabited the southern part of Greenland since 985. Communications between the Nordic settlements in Greenland and Iceland/Norway/Denmark continued until the beginning of the 15th century and were then lost for around 200 years. During the 17th century the relations between Denmark and the northernmost regions suffered, among other reasons, from the difficult national conditions related to the long-lasting European wars, in particular the wars between Denmark and Sweden. Recovering from these conditions and building a strong international position with large Danish battle and merchant fleets, the interest in Greenland returned.

In 1721 the Danish-Norwegian vicar Hans Egede (1686–1758) was sent to Greenland by the Danish King Frederik 4 to evangelize the descendents from the Vikings believed to be Catholics. To his surprise, Egede (Fig. 4) found the Inuit people instead of the Nordic and started to do missionary work among them. He also started trade with Greenland on behalf of the Danish King. Thus the relations between Denmark and Greenland were developing strongly during the 18th century and the frequent occurrence of auroras in Greenland became widely known and was mentioned in many publications dealing with Greenland (e.g., Egede, 1729).

Later in the 18th century the Swedish scientist Olof Peter Hiorter (1696–1750) noticed the relation between active

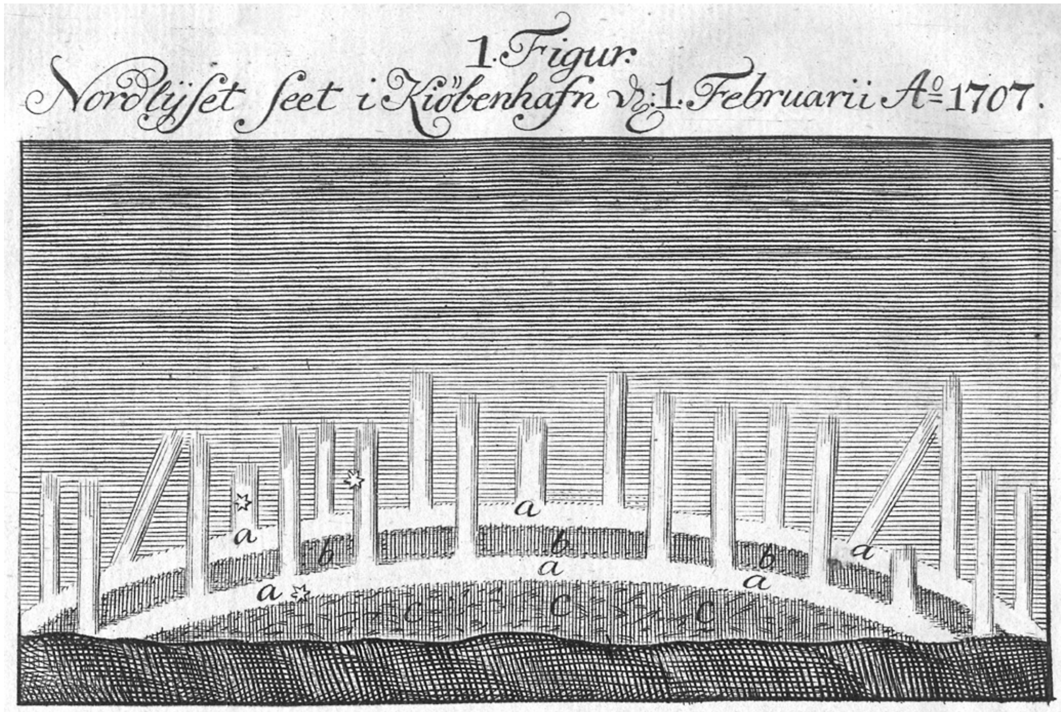

Figure 3. a.a.a: two bright transparent arcs through which the stars are visible; b.b.b: a dark space between the two arcs; c.c.c: a dark space where a dense rain cloud appeared. [*"a.a.a. Zwo helle durchsichtige Bogen, durch welche man die Sterne sehen konnte. b.b.b. Ein dunkler Zwischenraum zwischen den beiden Bogen. c.c.c. Ein dunkler Raum, der einer dichten Regenwolke hnlich war."*] (Ramus, 1745).

auroras and geomagnetic disturbances. Thus the important relation between auroras and geomagnetic disturbances was established through his publication in 1747 (Hiorter, 1747). One of the Danish missionaries in Greenland, Andreas Ginge (1755–1812) observed in Godthaab during the winter 1786–1787 the movements of a compass needle during auroral activity. His observations were published in 1788 by Thomas Bugge (1740–1815) (Bugge, 1788).

The relations between auroras and magnetic variations had now been established but still not explained. One theory explained the relation through the assumption that auroras were caused by magnetized cosmic dust entering the Earths atmosphere like miniature comets. It was not explained until the discovery of the magnetic properties of an electric current by Hans Christian Ørsted (1777–1851) who observed in 1820 the magnetic effect of an electric current. Ørsted published his discovery in the paper "Experimenta circa effectum conflictus electrici in acum magneticam." (Hafniæ, 1820) and sent his article (Ørsted, 1820) to prominent scientists all over Europe.

H. C. Ørsted was strongly interested in auroras and well aware of their intriguing magnetic properties. He proposed in 1823 at one of the meetings for national and international members of the "Royal Danish Academy for Science and Letters" (Kgl. Danske Videnskabernes Selskab) in his remarks on aurora theories ("Bemærkninger over Nordlysets Theorie", Ørsted, 1826) that "the luminous arc in large auroras has precisely the same orientation as that of an electrical discharge with corresponding magnetic effects." [*"at den lysende Bue af de store Nordlys netop har samme Retning som en elektrisk Udladning maatte have, der skulde staae i samme Forhold til Magnetismen"*]. The connection between auroras and geomagnetic variations was confirmed by other investigations, among others in the publication issued in 1827 (Hansteen, 1827) reporting the observations conducted by the Norwegian scientist Christopher Hansteen (1784–1873), professor at the University in Christiania (now Oslo), Norway.

H. C. Ørsted took two actions, which turned out to substantially promote auroral research in Denmark. Firstly, in 1827 on his initiative a permanent Meteorological Committee was formed comprising in addition to H. C. Ørsted also the botanist J. F. Schouw (1789–1852) and the physicist A. W. Hauch (1755–1838). The Committee issued the series of meteorological publications "Collectanea Meteorologica I–IV (1829–1856)". The Meteorological Committee initiated comprehensive observations both in Denmark and in the overseas regions, among others, in Iceland and Greenland. These observations comprised in addition to the usual weather parameters also occurrences of auroras, which at that time were considered an atmospheric phenomenon. The Committee was the forerunner of the Meteorological

Figure 4. Hans Egede (1686–1758) (Frederiksborg Museum).

Figure 5. Hans Christian Ørsted (1777–1651) (Frederiksborg Museum).

Institute (MI, now DMI) founded in 1872, which then took over the observational activities and data archives.

Secondly, H. C. Ørsted initiated scientific geomagnetic observations first, in 1833–1834, at the Technical University (Polyteknisk Læreanstalt), for which he was founder and for some years acting headmaster. Later, in 1842, the observations were located at the "Gyldenløve Fortress of Copenhagen". After 20 years of routine observations reported to the Royal Academy, the observatory was in 1862 relocated first to Rosenborg Fortress and later, in 1891, the magnetic observations were resumed by the Meteorological Institute from an observatory installed in the Botanical Garden in Copenhagen.

3 Preparations for the First International Polar Year

These activities initiated by H. C. Ørsted contributed to the combination of Meteorology, Geomagnetism and Auroral Research in Denmark for which the Meteorological Institute has been the dominant platform for more than a century. The Institute was since its start in April 1872 a member of the international meteorological organisation ("Organisation Météorologique Internationale", OMI) headed by the permanent committee (CMI).

The first director for MI, Niels H. C. Hoffmeyer (1835–1884), was a prominent member of "Polar Commission" of OMI. The interests for polar meteorological and geophysical research were at that time very high among the member countries that had territories located in the northern regions. Following a proposal from the Austrian scientist Carl Weyprecht (1838–1881) on international comprehensive meteorological and geophysical observations in the Arctic Regions, the Organisation at its second meeting held in Rome 1870 agreed to establish an International Polar Year to be held during 1882–1883 close to anticipated sunspot maximum in 1883–1884. The idea was further substantiated by CMI during the meeting in Bern, Switzerland, in 1880 and endorsed by the final meeting in Copenhagen in 1882 presided over by Niels Hoffmeyer (Fig. 6).

Altogether 13 countries were active in the Polar Year to send wintering meteorological-geomagnetism-aurora expeditions to remote locations in the Arctic regions. From Denmark the appointed location was Godthaab at the West coast of Greenland. Hoffmeyer employed Adam F. W. Paulsen (1833–1907) at the Meteorological Institute to lead the Danish expedition to Godthaab. Adam Paulsen was teacher at the Metropolitan School in Copenhagen and already known as the author of the popular book on physics: "Naturkræfterne" (Forces of the Nature), Vol. I–III, 1st Edn. (Paulsen, 1874–1879). In addition to Adam Paulsen the Danish expedition comprised 5 members, among others, marine lieutenant Carl Ryder (1858–1923), who some years later was leader of a similar expedition to East Greenland and also, like Adam Paulsen, became Director (successor to Paulsen in 1907) of the Danish Meteorological Institute.

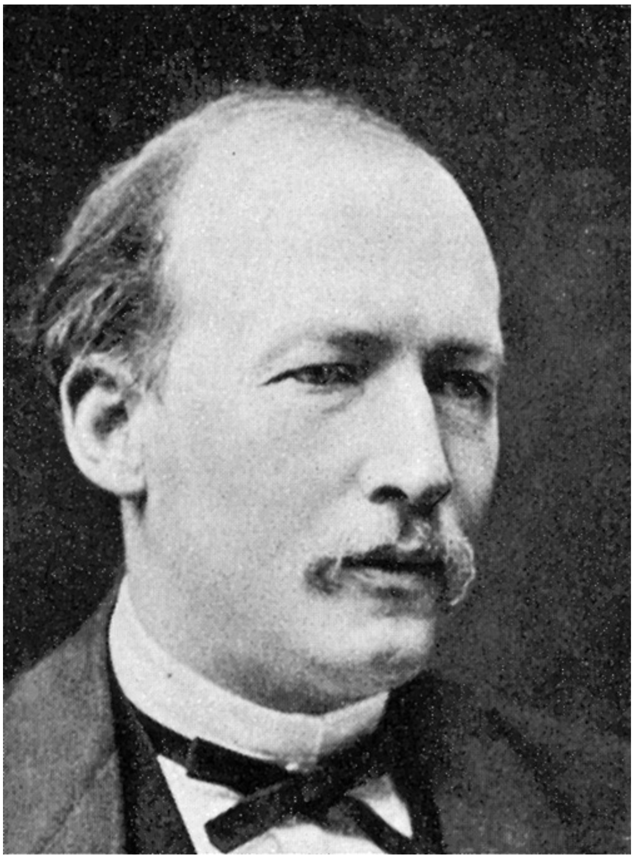

Figure 6. Niels H. C. Hoffmeyer (1835–1884) (MI, 1972).

Figure 7. Sophus Tromholt (1851–1896).

Furthermore, Hoffmeyer employed Sophus Tromholt (1851–1896) to analyze auroral data collected in Greenland. Born in Husum in Schleswig, Sophus Tromholt (Fig. 7) was Danish. He was a college-educated school teacher, interested in natural sciences, like astronomy and meteorology, and mathematics and strongly devoted to studies of the aurora. At the time of his association with the Danish Meteorological Institute he worked as a school teacher in Bergen. In the introduction to his work on auroral observations from Norway, Sweden, and Denmark (Tromholt, 1880) he writes (in English translation): "Among the problems reserved for future research in natural sciences to solve, the explanation of the mysterious aurora comes among the foremost. Connected with secret ties to the movements at the Sun's surface and to the Earth's magnetic power, this splendid light phenomenon defies every attempt from Science to provide answers to the questions earnestly addressed to the observer." [*"Blandt de Opgaver, som det er Fremtidens Naturforskning forbeholdt at løse, indtager Forklaringen af Nordlysets gaadefulde Væsen en af de første Pladser. Knyttet med hemmelighedsfulde Baand til Bevægelserne paa Solens Overflade og til Jordens magnetiske Kræfter, trodser dette herlige Lysfænomen endnu stadig ethvert Forsøg fra Videnskabens Side paa at besvare de Spørgsmål, som det saa indtrængende retter til Iagttageren."*]

To provide a basis for this work he circulated 600 letters to vicarages all over Norway and to many Norwegian sea captains with a request to report on occurrences of auroras and with an enclosed schematic form to shape a homogeneous collection of material. In addition he collected notes on auroral observations from Norwegian, Swedish, and Danish meteorological stations provided through the Nordic Meteorological Institutes (Prof. Mohn in Christiania, Prof. Rubenson in Stockholm, Prof. Hildebranson in Upsala, and Capt. Hoffmeyer in Copenhagen) (excellent Nordic collaboration) and he also made his own comprehensive auroral observations mainly from Bergen. Altogether, he collected 839 simultaneous observations from 132 stations in the three Nordic countries over 154 nights with auroras occurring during 1878–1879. These observations are described and analyzed in his report published in 1880 (Tromholt, 1880). The instrument used to observe the parallaxes to auroras from two observing sites is shown in Fig. 8 and represents a considerable improvement over previous methods (e.g., Fearnley, 1859).

In his publication (Tromholt, 1880) Tromholt carefully reports all the observations and tries to extract general features of the auroras from the comprehensive, but rather inhomogeneous data material. Now we know that many of his conclusions in this report were mistakes. Nevertheless, they probably served as the initial theses both for Tromholt himself in his further brilliant auroral analyses, but also for the other

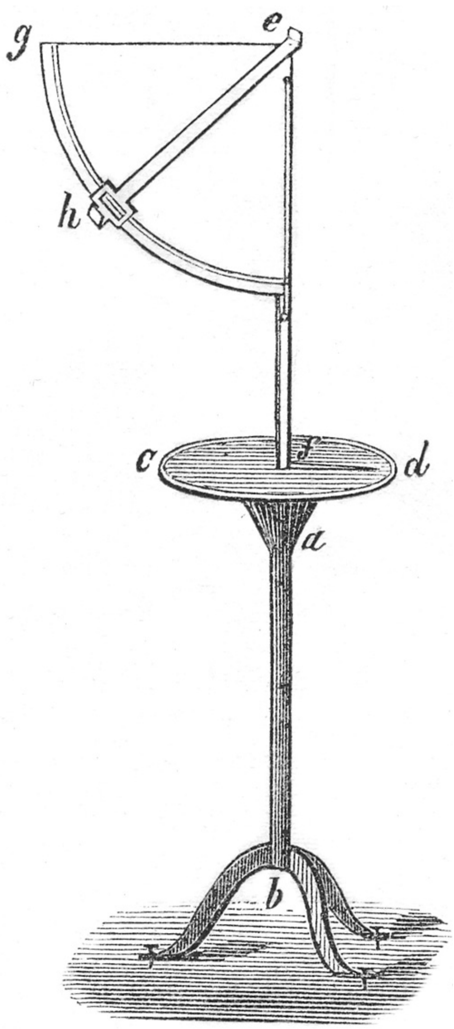

Figure 8. Tromholt's Instrument for sighting auroras (Tromholt, 1880).

Danish scientists, primarily Adam Paulsen, with whom he worked up to the Polar Year Expedition. Thus his observations and conclusions shall be briefly outlined here.

On the relations between auroras and weather, Tromholt notes (Tromholt, 1880, p. 115) that the auroras could have condensing or dissolving effects on the humidity of underlying air masses and claims having strikingly proven the relations between auroras and clouds. From the differences in simultaneous observations of auroras from neighbouring places Tromholt further concludes (pp. 130–131) "that auroras in many cases are quite localized and appear close to the Earth's surface." [*"at Nordlyset i mange Tilfælde er et temmelig lokalt Fænomen, og at det ofte optræder i ringe Høide over Jordoverfladen."*]. Tromholt reports a number of cases of what he considers to be reliable information on auroras observed below mountain peaks, below low nimbus-like clouds, or even extending from trees at the ground.

Through the full interval of auroral observations from 1 September 1878 to 30 April 1879, Tromholt examines their relations to geomagnetic observations made twice a day, at 09 and 14 hours, from Christiania (Oslo) by Professor F. Fearnley. He found (pp. 138–139) "no evident relation between the levels or changes in the magnetic instruments and the occurrences of auroras". [*"har det dog ikke lykkedes mig at finde nogen paafaldende Sammenhæng mellem de magnetiske Instrumenters Stand eller Forandringer og Nordlysets Optræden."*]

Tromholt has apparently not himself observed sounds from the aurora, but he faithfully refers (Tromholt, 1880, pp. 140–141) to trustworthy observations made by, among others, Professor Hansteen (1784–1873), and also his own father, J. P. Tromholdt, who reported to have heard sounds from auroras (Tromholdt, 1860). Sophus Tromholt (1880, p. 140) concludes that "one can not possibly deny the existence of this mysterious sound." [*"at man umuligt kan benægte Tilværelsen af denne gaadefulde Lyd."*]. In a later publication (Tromholt, 1885c), he refers to various reported observations of auroral sounds.

One conclusion in his work (Tromholt, 1880) is quite correct. Tromholt states (p. 138) that even in a solar minimum year, and in a limited region like the three Nordic countries, there will hardly be a single night without the occurrence of aurora somewhere within the region. And he claims this discovery to be one of the most important results of the comprehensive auroral observations made during the winter 1878–1879. In his further auroral studies he collected reports of observations of auroras prior to 1878. This material (Tromholt, 1902) was edited by J. Fr. Schoeter and published in 1902 after Tromholt's death in 1896.

The comprehensive work (Tromholt, 1880) and his contact with director Niels Hoffmeyer probably paved the way for his involvement with the Danish Meteorological Institute to conduct analyses of auroral recordings from Greenland in preparation of the Polar Year Expedition. Among the observational activities and data archives taken over in 1872 by the Meteorological Institute from the Meteorological Commission established by H. C. Ørsted were various auroral observations. Observations of auroras were made from Stykkisholm in Iceland (1846–1873) and from Greenland by Bloch from Godthaab (1841–1846) (Bloch, 1856), by Rudolph from Jacobshavn (1840–1851) (Rudolph, 1856), by Fritz from Ivigtut (1875–1880) (S. Fritz, 1881), Upernavik (1874–1880), and Sukkertoppen (1875–1876 and 1878–1879). Most important are the observations made from Godthaab by Samuel Petrus Kleinschmidt (1814–1886) during the years from 1865 to 1882.

Samuel Kleinschmidt (Fig. 9) was a teacher at the College of Education in Godthaab and well-known in Greenland and Denmark for his comprehensive efforts to describe the Greenlandic language and form its vocabulary and grammar (see Wilhjelm, 2001). In addition, Kleinschmidt was a careful meteorological observer and profoundly interested in

Figure 9. Samuel Petrus Kleinschmidt (1814–1886) (from Wikipedia).

auroras. Almost every day during the years from 1865 to 1882 he observed and reported on the weather three times a day, in the morning at 04–05, at noon around 12–13, and in the evening at around 21 hours local time. Among other parameters he reported on the cloud coverage – an important parameter in relation to auroral observations. During the morning and evening hours he also observed and reported on occurrences of auroras. In addition to reporting on the location and orientation of the aurora he meticulously reported on the characteristics of the observed auroras. He formed his own methodical system composed of letters and numbers to characterize the location in the sky, the orientation, the shape, and the dynamics of the observed auroras.

Sophus Tromholt immediately recognized that observations with these characteristics would form an exceptionally stringent description of the occurrences of auroras. Adding to the systematic characterization of auroras the extended interval (1865–1880) of very regular observations in the morning (~05) and evening (~21) of almost every day and the careful simultaneous and co-located meteorological observations (e.g. of cloud cover), makes this series of observations a unique resource for analyses of auroras.

Tromholt's analysis of Kleinschmidts extensive observations from Godthaab supplemented by shorter series of auroral observations from Stykkisholm, Upernavik, Sukkertoppen, and Ivigtut was published in Danish and in French (for the international community) in the Annual Report for 1880 (issued in 1882) from the Meteorological Institute, and also as a separate extract in Danish and French with the title "Om Nordlysets Perioder efter Iagttagelser fra Godthaab i Grønland" (Sur les périodes de l'aurore boréale) (Tromholt, 1882a). In the introduction (p. V) to his analyses Tromholt notes that "the investigations have given me, in several respects, the peculiar result, briefly spoken of, that everything regarding the varying frequency of auroras in Godthaab is in contrast to occurrences at more southerly latitudes". [*"Undersøgelsen af de Godthaab'ske Nordlys har ført mig til et i flere Henseender mærkeligt Resultat, der kort kan udtales saaledes, at alt, hvad der henhører under Nordlysets vexlende Hyppighed, i Godthaab udviser et Modsætningsforhold, til hvad der finder Sted paa sydligere Breder.*"]

In his statistical analyses Tromholt utilized the precise local reports on cloud coverage to correct the numbers of observations of auroras thus making the material more representative of the real number of occurrences. He had noticed (p. IX) that "the number of observed auroras is nearly inversely proportional to the level of cloudiness." [*"det observerede Nordlysantal er næsten nøjagtig omvendt proportionalt med Skymængden.*"] (cloudiness on the meteorological scale from 0 to 4 or, since 1877, on the scale from 0 to 10). This relation, he notes, contradicts the results published by Weyprecht (1878, pp. 35–36) that months with large amounts of clouds have disproportionally large numbers of auroras and his conclusion that "the clouds have a definite association with the auroras; it appears, as if the cloudiness favours the development of auroras." [*"die Wolken doch in einem gewissen Zusammenhange mit den Nordlichtern stehen, und zwar würde es erscheinen, als begünstige die Bewölkung die Entwicklung der Nordlichter.*"]

With the comprehensive and homogeneous data material collected by Kleinschmidt, Tromholt analyses the daily and seasonal variations in the geographical distribution and the occurrence frequency of auroras and the variations with sunspot activity expressed through the sunspot numbers (e.g., Wolf, 1858; Lovering, 1860, 1868). He obtained these data by direct correspondence with R. Wolf. His most important result, illustrated in Fig. 10, was (p. XII) that there "not only is no direct parallelism, but on the contrary an almost complete contrast between aurora and sunspot occurrence frequencies." [*"at der her ikke alene ikke er nogen Parallelisme, men tværtimod en næsten fuldstændig Modsætning mellem Nordlys- og Solplethyppighedens Gang.*"]. Tromholt divides the observations from Godthaab in evening and morning auroras and concludes that the inverse relation to the sunspot cycle is reproduced for both groups but most clearly for the evening occurrences of auroras. The corresponding analyses of auroral observations from the shorter and less homogeneous series from the other stations in Iceland and Greenland gave corresponding results, which lead Tromholt to conclude

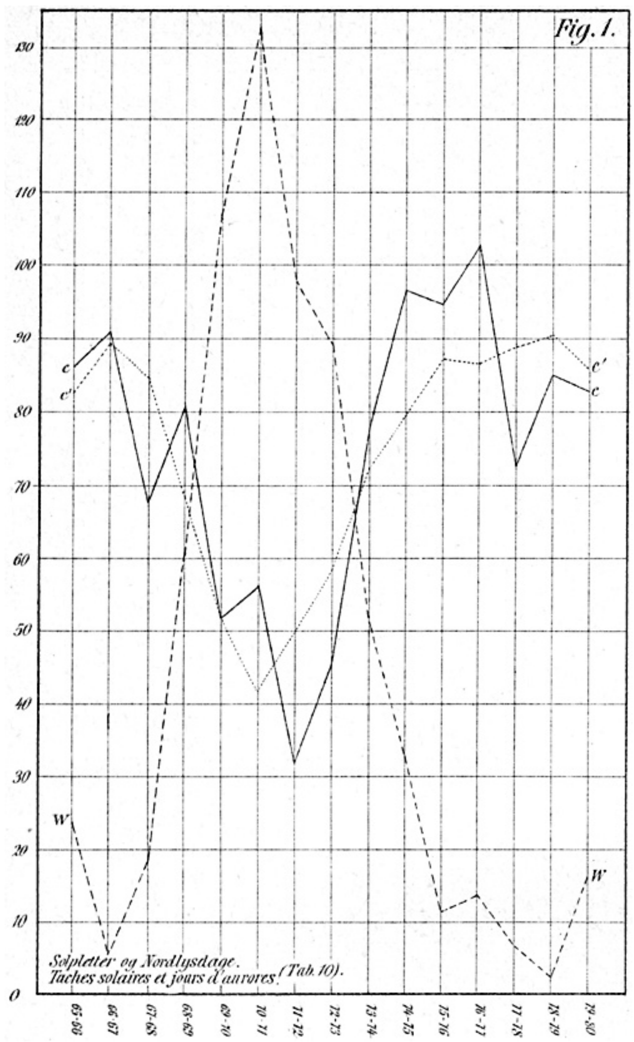

Figure 10. Relations between Wolf's sunspot number (dotted line) and no. of auroral nights (heavy line). Thin line indicates equivalent values of auroras (Tromholt, 1882a).

(Tromholt, 1882a, p. XVII) that "the auroral observations in our possession from Polar Regions can only contribute to strongly substantiate the law derived with high certainty from the observations from Godthaab." [*"at de Nordlysiagttagelser, vi besidde fra Polaregnene, kun kunne bidrage til i høj Grad at styrke den Lov, som de Godthaab'ske Iagttagelser med saa stor Bestemthed antyde."*].

For the seasonal variation Tromholt concludes in agreement with Weyprecht (1878, p. 35) that the auroras in arctic regions have their maximum occurrence close to solstice, which is contrary to the distribution at middle latitudes where the occurrence frequency is maximum at equinoxes. Tromholt accepts the explanation given by Weyprecht (p. 35) that "the region of highest occurrences of auroras rises towards the North at winter solstice and retreats to the South at equinoxes" [*"das sich der Gürtel grösster Häufigkeit des Nordlichtes gegen das Wintersolstitium gegen Norden hebt und sich gegen die Äquinoctien gegen Süden senkt."*]. Tromholt extends the theory to also comprise the solar cycle variation such that the region of highest occurrences moves southward (equatorward) at sunspot maximum and retreats northward at minimum. With present-day knowledge, both trends in the location of the auroral zone are correct but not the complete story.

Tromholt took the theory of a moving belt of maximum auroral occurrence one step further to include the daily variations. Since he was aware that Godthaab is located in the northern outskirt of the auroral belt such that auroras in the northern sky are rare occurrences (contrary to the situation for the observations made by Weyprecht close to Franz Joseph Land north of Russia), he divides the southern auroras in two groups, one far south and another closer to zenith and considers for the two groups the relation between evening and morning auroras. Statistically, he finds that the frequency of occurrences within the two groups is the same for evening auroras whereas the occurrences for morning auroras are much more frequent close to zenith than further south. From these observations he concludes (Tromholt, 1882a, p. XXXVII) that "This important and with great certainty derived result gives evidence that the auroral zone in its daily walk travels northward during the night." [*"Dette vigtige og med stor Bestemthed fremtrædende Resultat vidner om, at Nordlyszonen ogsaa i Døgnets Løb foretager en Vandring, saaledes at den i Løbet af Natten bevæger sig mod Nord."*]. In Tromholt's view this regularity also explains the daily variations observed by Fritz (1874, 1881) for auroras at lower latitudes where the occurrences maximize a few hours before midnight and then decrease during the following hours. This conclusion is clearly an indication that the region of maximum occurrence of auroras has a daily variation in latitude. However, it was not until 1963 that the concept of an instantaneous auroral oval, where the region of maximum occurrence of auroras in the day is located 8–10° further poleward than at night, was suggested by the Russian scientist Y. I. Feldstein (Feldstein, 1963) and now agreed and confirmed through auroral observations from ground and space.

Contrary to his previous work (Tromholt, 1880), in his publication on the periods of the aurora (Tromholt, 1882a) based on data from Greenland, Tromholt does not discuss the height of the aurora. The possible relations to magnetic variations are referred to on the basis of different sources. With regard to auroral colours and possible sounds, the publication refers to the remarks by Kleinschmidt where he notes that the aurora usually is colourless like the moonlight except for the rare occurrences of red auroras and occurrences of auroras in strong motion where red and green colours are observed. Further (p. XXXI), it is also faithfully referred (this time without his comment) that Kleinschmidt states "that I never ever have observed any sound related to the aurora, despite my hearing generally has been quite good." [*"at jeg*

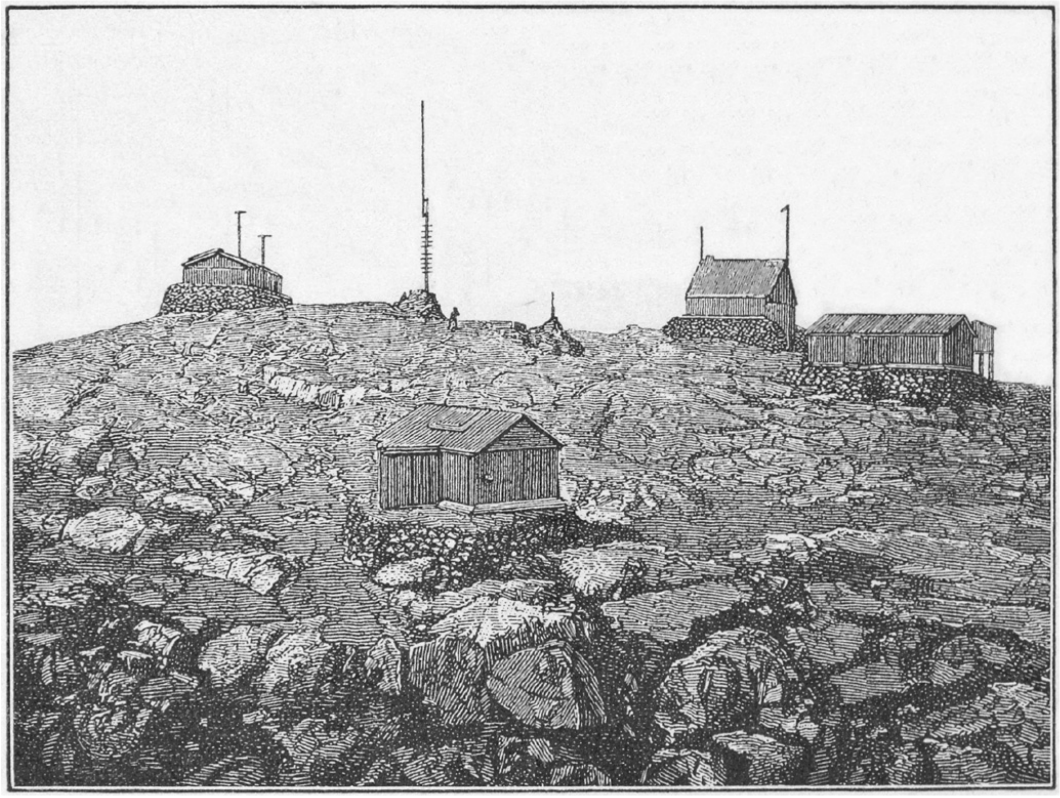

Figure 11. Polar Year Observatory in Godthaab (1882–1883) (drawing, Paulsen, 1893).

aldrig nogensinde har bemærket nogen Lyd forbundet med Nordlyset, uagtet min Hørelse i Almindelighed har været ret god."]

4 The Danish Polar Year Expedition to Godthaab 1882–1883

In the foregoing chapter the analyses of auroral observations from Greenland by S. Tromholt have been discussed extensively since this work was probably most valuable for the planning of the expedition and definition of its tasks. Most likely, the leader of the expedition, Adam Paulsen, as well as C. Ryder, and the other four members of the expedition team (Paulsen, 1893a, Introduction, p. 4) had little previous experience with auroral observations and handling of auroral data. Much of their knowledge of polar auroras was based on the observations reported by Weyprecht (1878). The instrumentation and the later reports from the expedition (Paulsen, 1884, 1886, 1889, 1890, 1893a, b, 1894) indicate that its primary objectives related to auroras were observations of the relations between aurora and geomagnetic variations as well as possible relations between the aurora and the atmosphere including the heights of auroras.

The Danish Polar Year Expedition left for Godthaab by ship on 17 May 1882. They brought materials to construct 5 buildings to house the instruments and the 6 members of the expedition at selected places in Godthaab (Fig. 11). The building for the magnetic observatory was placed on a small mound of pure gneiss with little content of iron. Other buildings to house the meteorological instruments and living quarters were placed at safe distances in order not to disturb the magnetic observations. The geographical coordinates for the station were (64°10′48″ N, 51°40′0″ W). (Today this location is called "Kirkebakken" (Church Hill) and a statue of the missionary Hans Egede is placed on its top).

For the magnetic observations the expedition brought an Edelmann-Munich theodolite, a Kew inclinometer, an Edelmann variometer, and an Jürgensen-Copenhagen variometer. The basic magnetic elements for the station were estimated to be: $H = 0.968$ Gauss, $I = 80°15'$, $D = 57°45'$. The seasonally varying regular daily changes in the elements were also determined. On the possible relations between auroras and magnetism, Paulsen notes (Paulsen, 1884, pp. 24–25) that the quiet or weak auroras in general gave no effects on the magnetic deflection while strong and variable auroras would give strong oscillations in the magnetic component.

In his publication in Danish on the results of the Polar Year expedition (Paulsen, 1890), Paulsen adopts the classification defined by Weyprecht (1878, pp. 2–10).

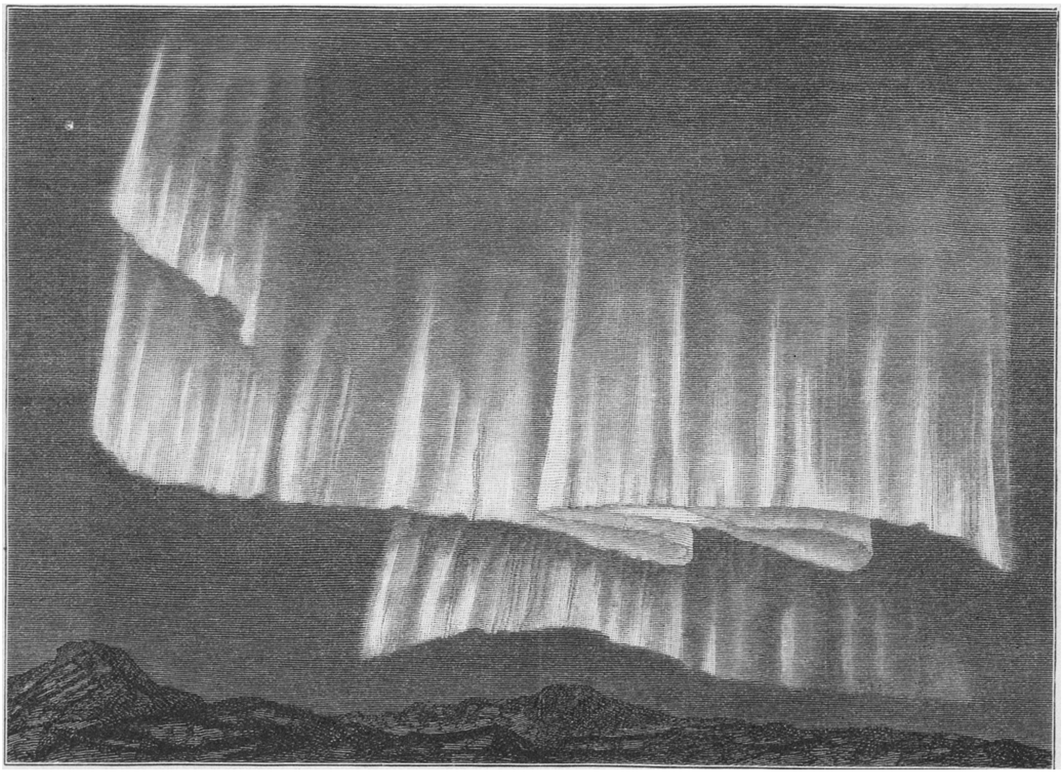

Figure 12. Aurora (folded bands) observed from Godthaab to the South on 15 November 1882 at 00 h 10 m (drawing, Paulsen, 1893a).

i. "Bögen" (arc) shaped like a rainbow; when fully developed it would reach the horizon at both ends.

ii. "Bänder" (bands) arcs or curtains with folds and often strong motions.

iii. "Fäden" (rays) elongated long rays often combined in bundles.

iv. "Krone" (crown) overhead bundle of rays all pointing towards a common point in the sky.

v. "Dunst" (haze or fog) brightenings without specific contours.

A preliminary report on the expedition was issued in 1884 (Paulsen, 1884). Later, the observations were meticulously reported by Paulsen in 1893 (Paulsen, 1893a, b). Totally, during the Polar Year expedition to Godthaab, the auroral observations during 14 August 1882 to 31 August 1883 comprised 261 cases of arcs, 37 draperies, 160 rays, 284 bright auroral clouds, and 36 cases of auroral crowns. A résumé of the description given in Paulsen (1890, pp. 312–314) illustrates the typical development of auroral activity: Most often a steady arc appears in the south-eastern direction with its top in the magnetic meridian and both ends reaching the horizon. Then, one arc after the other moves northward, past zenith and eventually retreats in the opposite direction. Sometimes the arcs are "incomplete" as their "feet" appear to be detached from the horizon. They now have the shape of freely "flying curtains" often with strong motions and formations of folds and rays. When the rays are interconnected they converge at the top and may form a giant fan. The curtains often appear to be flapping as if the wind produces wavy motions in the folds. The brightness is always strongest at the folds. With strong motions the lower border could display red and green colours. Otherwise the colours of the arctic auroras are white sometimes with a pale greenish tone.

Paulsen, in his description of auroras (Paulsen, 1890), dwells on the zenith arc described by Kleinschmidt in his classification. This type of arc, he notes, starts in the northeast, passes through or close to the zenith, and ends in southwest. Often the zenith arc is not "complete" (reaching ground at both ends) but detached at the ends to form vivid curtains or bands of rays. Sometimes strong whirls are formed in the middle of which no auroras are seen. A crown may now appear due to the perspective effect of the bundle of rays aligned with the magnetic inclination needle. Hence the crown, he concludes (Paulsen, 1890, p. 314) correctly, is not a separate auroral form.

The instrumentation used for auroral observations included aiming devices of the type used earlier by Tromholt (Tromholt, 1880). Tromholt's instrument had a gun-sight used to aim at the aurora mounted on a turnable pointer

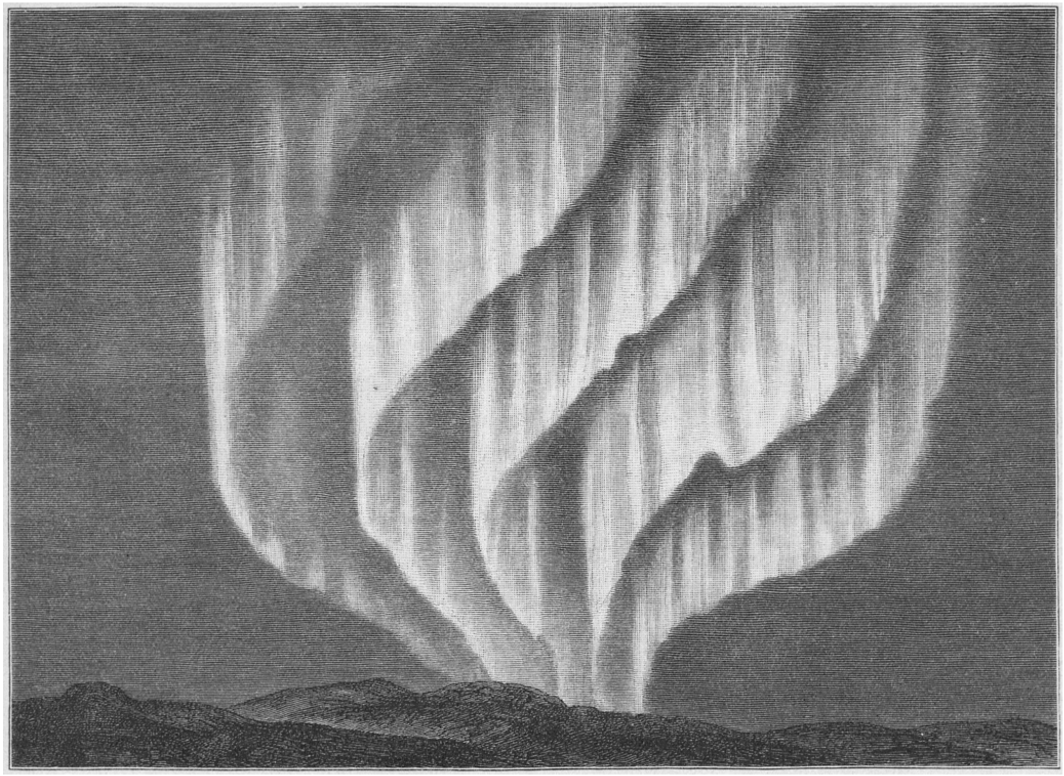

Figure 13. Auroras (multiple rayed bands) observed to South-West from Godthaab on 15 November 1882 at 00 h 30 m (drawing, Paulsen, 1893a).

whose azimuth and inclination could be read on angular scales. In addition, a shade was mounted on the pointer such that the auroral light would disappear when the pointer was aiming below the auroral curtains. Many of the greatest auroras were carefully plotted on charts. For that purpose, star maps to display the sky visible over the horizon of Godthaab had been prepared in advance on transparent sheets. Adjusting for the sidereal time made it possible to map the auroras from their positions relative to the stars. One such example observed on 5 November 1882 at 06 h is displayed in Fig. 14.

For the auroral height observations the expedition constructed an additional shelter at the opposite coast of Godthaab fiord at a distance of 5.8 km in the direction of the magnetic meridian. Between the main station and the shelter, communications were made by light signals. The aiming devices were mounted at both the sighting stations and the pointers allowed to turn only in the magnetic meridian plane. Thus, from reading the angles to the lower border of an aurora simultaneously at both places, the height could, in principle, be calculated by simple triangulation. The lowermost heights of 31 auroral arcs were determined. For 9 of these, the results were rejected since the parallax was too small considering the uncertainty in the observations (the heights would exceed 68 km). Of the rest, 8 cases gave heights between 19 and 68 km, while the remaining 14 cases gave heights between 0.6 and 9.8 km.

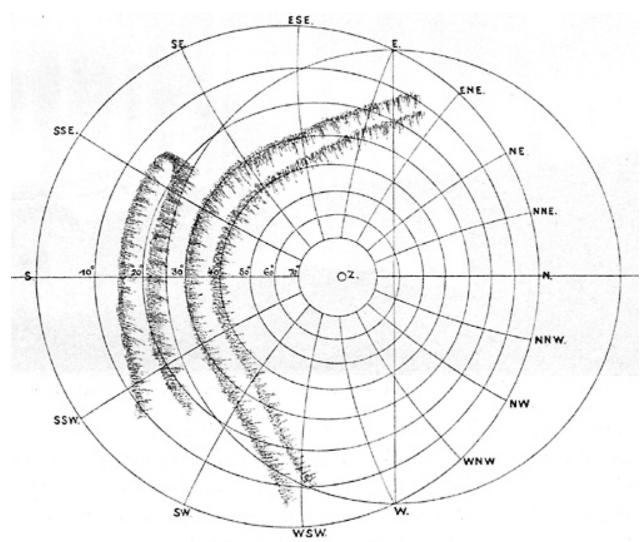

Figure 14. Plot of auroral forms observed on 5 November 1882 at 06h from Godthaab (drawing, Paulsen, 1893a).

From the observations reported in Paulsen (1889, 1893a, b) it appears that all parallaxes were measured to the south from both observatory sites. Paulsen (1893b) discusses carefully the uncertainty in the observations and was convinced that the results were reliable. Furthermore, Paulsen (1893b, Part I, p. 8) mentions that he has observed several auroras below cirrus clouds and draws attention to the observations on 17 October 1882 of a bright "auroral cloud" seen at altitudes of 0.6–1.4 km. The sighting instruments were later used in similar observations made by Garde and Eberlein from Nanortalik in 1885 with a base distance of 1249 m. Their observations gave heights between 1.8 and 15.5 km for the lower border of auroras (Garde, 1889). In his conclusions Paulsen (1893b, Part I, p. 14) states that within a region of width at least 4° extended across Greenland auroras could appear in all heights all the way down to the Earth's surface.

In his description of the auroral observation, Paulsen (1889, 1890, 1893a, b, 1894, 1895c, 1896) notes in several places (e.g., 1990, p. 313), that the auroral activity often ends in a giant bright cloud usually hovering at great heights, but sometimes appears like a wisp of smoke extending from the ground. Combined with the recordings of the low auroral heights these observations have substantially influenced Paulsen's views on the origin and cause of the auroras. In his view, which was possibly influenced by similar thoughts in the early works of Tromholt (1880), the high arctic regions were the "home of the auroras" where they would extend all the way from the greatest heights to the ground, while at lower latitudes they would only occur at great heights. He considered like the Swedish scientist Edlund (1878) auroras to be an electrical phenomenon in contrast to theories of "cosmic dust meteors" or "luminescent clouds" (Loomis, 1868).

In order to explore this aspect, the expedition also conducted observations of atmospheric electricity. A Thomson, model Mascart, electrometer whose deflection was calibrated by the voltages from batteries of Zinc-Glycerine galvanic elements was connected to a wire antenna carefully isolated from the surroundings. Such observations are heavily influenced by the humidity of the air, and the results from Godthaab are largely inconclusive since they only indicate the seasonal variations in the atmospheric conditions. Paulsen was aware of the problems and carefully watched the electrometer during auroral activity without observing deflections that could be related directly to the auroras. However, he states as a general rule that in periods of strong auroral activity the electrical field near ground weakens.

The electrical discharges could also conveniently explain the magnetic effects associated with auroras. During the Polar Year expedition to Godthaab direct observations of magnetic deflections during auroras were rather sparse, since the auroral observations and the magnetic observations were made from different buildings. However, Paulsen (1893a, Part IV) states that the Polar Year observations are in agreement with later observations made by Vedel on Ryder's expedition in 1891–1892 to Ile de Danemark (70°27′ N, 26°10′ W) near Scoresbysund at the East coast of Greenland. From observations of the magnetic deflections during approaching auroras, Vedel (1895) reports that the deflection is constantly westward when the auroral arc is moving from the South towards the station. When the aurora reached the zenith the magnetic deflection would oscillate strongly around the position it had before the aurora appeared. When the aurora then moved further North away from the station the deflection would be eastward. Paulsen (1893a, Part IV) notes that this variation is in agreement with his suggestion of an upward current from ground to great heights associated with auroral rays.

5 Dispute between Paulsen and Tromholt

Tromholt was not directly involved in the Danish Polar Year Expedition. He was at that time preparing auroral observations from North Norway and Finland and he also wrote a number of popular articles in the monthly magazine "Naturen" (1882b, No. 6, 7, 8, and 9) and (1883, No. 6) issued in Christiania. Here, he repeats his former theories on the daily, seasonal and sunspot-related periodicity in the location of the region of maximum auroral occurrences. He also reports on auroral height estimates based on triangulation of the strong aurora observed on 17 March 1880 from which he determines an average height of 147 km. Furthermore, he reports on the establishment of a new auroral observatory in Kautokeino in Finnmarken 100 km south of the Norwegian observatory in Bossekop for simultaneous observations of cloud coverage, and auroral form, position, azimuth, intensity, and motion. It seems (Tromholt, 1883) that Tromholt now casts doubt on previously reported observations of auroras in low altitudes.

Having analyzed the auroral observations from the Polar Year expedition, Paulsen starts to develop his own view on the aurora and its cause. As mentioned above he firmly believed that arctic auroras were related to electrical currents reaching to ground at high latitudes. He also examines Tromholt's theories on the periodic motions of the region of maximum auroral occurrences. In his bulletin to the Royal Danish Academy from 1889 (Paulsen, 1889), he completely rejects the hypothesis on the daily oscillation in the latitude of maximum auroral occurrences and casts doubt on Tromholt's theories on the seasonal and sunspot related periodic variation in the latitude of maximum auroral frequency.

Born from considerations of auroras caused by discharging of a surplus of negative electrical charge at high altitudes, the main argument (Paulsen, 1889, p. 26) for his new concept is the suggested rule that "a more active development of auroras in temperate regions reduces the auroral activity in the proper auroral zone)." [*"Une evolution plus active des phénomènes de l'aurore boréale dans les régions tempérées ralentit l'activité aurorale dans la zone propre des aurores"*]. Thus, if the auroral activity is generally strong, particularly at lower latitudes, then the activity at the highest latitudes must weaken. Paulsen bases his view not only on the auroral observations from the Godthaab expedition (1882–1883) but also he examines the series of auroral observations made by Kleinschmidt from Godthaab and the observations from Nanortalik, Ivigtut and Jacobshavn, also used by Tromholt. In both data sets he finds a daily variation in the absolute intensity and occurrence frequency of auroras with a maximum in the evening hours (around 9–10 p.m.). In his opinion, when the auroral activity in general decreases in the morning hours then the more northerly auroras are no longer suppressed by the more southerly activity. Paulsen also argues the other way around: if the variation was just a daily oscillation in latitude of the auroral region then the intensities and occurrence frequencies should be the same for morning auroras at high latitudes as those of the midnight auroras at lower latitudes.

For the seasonal variations Paulsen (1889) argues that the absolute intensity and occurrence frequency of auroras generally maximize close to winter solstice at most latitudes. Again, from high activity during midwinter follows a reduction in the occurrences and intensities of the arctic auroras at that time which could in his view at least partly explain the apparent motion of the latitude of the auroral belt. For the variation in the auroral frequency with number of sunspots, he acknowledges the minimum in the occurrence frequency of arctic auroras at high sunspot numbers without specifically attributing the variation to a motion in the latitude of the belt of maximum auroral activity (maximum zone).

These arguments and the fairly strong criticism of Tromholt's theories, which he explicitly mentions quite often, are repeated and further sustained in several of Paulsen's publications in the following years (e.g., Paulsen, 1893c, 1894, 1896). Tromholt (1892), in an article in Petermanns Mittheilungen, argues against Paulsen's criticism and also mentions his new observations from Finnmarken, which have been reported in the book: Under the Rays of the Aurora Borealis, London (Tromholt, 1885b) (in a Danish Version: Under Nordlysets Straaler (1885a)). From this book it appears that Tromholt, based on triangulation of synchronous sighting observations from Bossekop and Kautokeino, was the first to reliably deduce the heights of the lower border of aurora (long before the Norwegian scientist Störmer's excellent photographic technique took over). From a series of observations made during the winter 1882–1883 an average altitude of 113 km was found. A remarkably precise result consistent with much later height analyses, e.g., by Størmer.

6 Further development of Paulsen's aurora theories – the auroral spectrum

Paulsen (Paulsen, 1893b, part IV, p. 14) was aware of the recent advances in laboratory spectroscopy and of the observations in 1867 of the spectrum of auroral emissions made by the Swedish scientist Anders Jonas Ångström (1814–1874). Ångström had in 1867 identified in the auroral spectrum the strong green line (557.7 nm) and later the double red line (630.0 nm, 636.4 nm) (Ångström, 1869). Laboratory experiments with electrical discharges in rarefied gases had convinced Paulsen that the auroral light was the result of electrical discharges in the atmosphere. With the simple spectroscope used in Godthaab during the polar year the expedition only observed the dominant green auroral line (557.7 nm), which is also present in airglow. Hoping to detect further lines Paulsen even made efforts with very low auroras to direct the spectrometer towards the rays and shield the aperture against false light. But only the usual green line was observed.

In the succeeding publications, with his analyses of the Polar Year data and other auroral observations, Paulsen was troubled with the lack of laboratory verification of the green line. He was aware that the red line(s) from oxygen emissions and also the blue/violet line(s) from discharges in nitrogen gas could be reproduced in experiments. But the green line could not be reproduced in laboratories (the vacuum technique was not developed to produce the very low air pressure needed for the oxygen green line excitation). Thus Paulsen (Paulsen, 1893b, part IV, p. 15) considered the possibility of a hitherto unknown gas present in the highest atmosphere, but rejected this hypothesis and accepted Ångströms theory that the green line was produced by some fluorescence in the atmosphere caused by the effect of the radiation by another, probably ultra-violet, line in the auroral spectrum.

Thus, Paulsen (1896) had developed a comprehensive theory for the generation of auroras: Through the effects from solar illumination at the uppermost layers of the atmosphere, particularly in the equatorial regions, an amount of negative charge was formed in the daytime. The excess amount of negative charge would then drift towards the higher latitudes forming a current system at high altitudes. In the arctic regions the invisible "cathode rays" emitted from the negative charges would follow the magnetic field lines all the way down to the ground. During their descent the cathode rays in the discharge would cause the molecules of the atmosphere to glow, emitting light in the different lines of the auroral spectrum. The red and blue lines were directly related to the cathode rays whereas the green line was caused by fluorescence related to some undetected radiation most likely in the ultra-violet part of the spectrum.

The important issues for future expeditions would then be further investigations of the auroral spectrum, particularly in the ultra-violet range, and investigations of the electric fields and magnetic effects associated with auroras. Thus, the preparation of the expeditions to Iceland (1899–1900 and later to Finland (1900–1901) could now be started from specific goals.

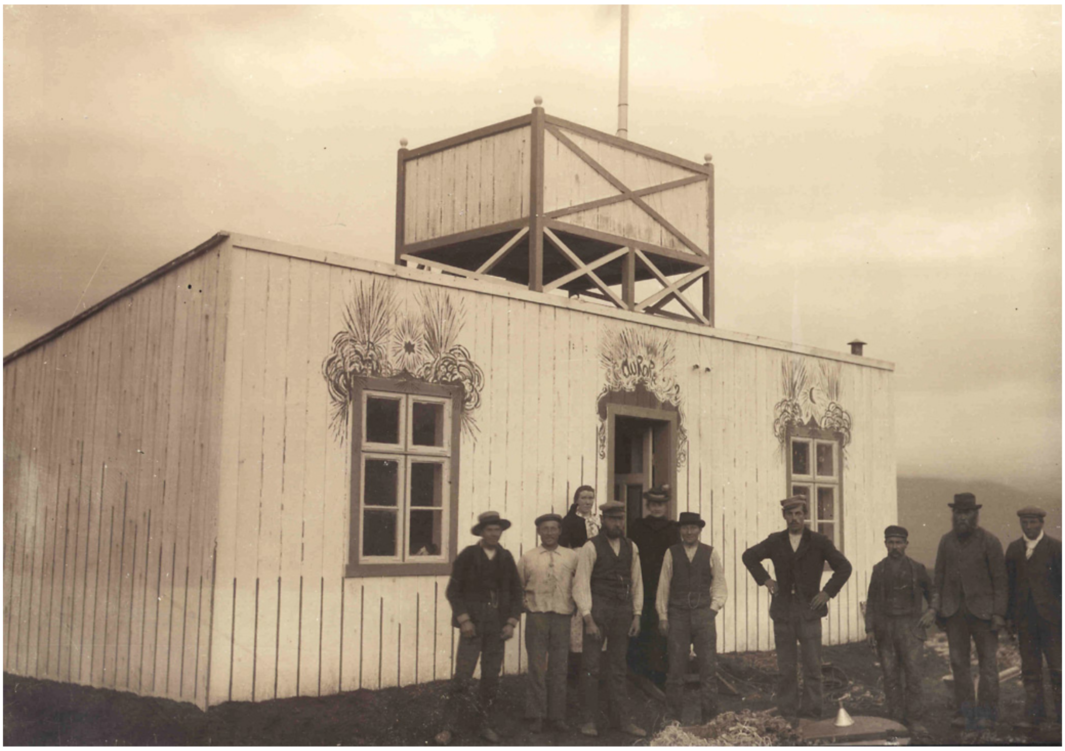

Figure 15. "Aurora". Expedition base hut: Weather station, Painters studio, and Auroral observatory (Photo, DMI).

7 The Danish aurora expedition to Iceland 1889–1900

As Adam Paulsen had finished his works mainly based on the observations made on the Polar Year expedition to Godthaab he felt the need for further auroral observations for studies particularly of the auroral spectra and the electric and magnetic effects related to auroras. An expedition headed by G. C. Amdrup was sent to East Greenland and made magnetic observations during auroral activity (Holm, 1889; Amdrup, 1904; Hjort, 1904; Ravn, 1904). Another new auroral expedition to Greenland was planned. However, shortly before departure on 30 July 1899 the destination was changed to Akureyri at the north coast of Iceland, which was located as favourably as Greenland for auroral studies and more easily accessible.

Paulsen was now an elderly man, at an age of 66 years and visually impaired, but he took command of the expedition, which included three young members: Dan Barfod la Cour (1876–1942), student in physics at Copenhagen University, Ivar B. Jantzen (1875–1961), student at the Polytechnical University, and count Harald Moltke (1871–1960), an artist painter, who had been illustrator for the geologist K. V. J. Steenstrup (1842–1913) on a geological expedition to the Disko island in Greenland in the summer of 1898.

The expedition arrived by the ship "Botnia" to Iceland on 16 August 1899. Under supervision by Jantzen the expedition brought materials for the construction of buildings both for a magnetic observatory and for a combined weather station and auroral observatory to house further instruments. The observatory building shown in Fig. 15 was constructed in the outskirt of the small Icelandic town, Akureyri, and (not surprisingly) named "Aurora".

In addition to the main station a small shelter was constructed at the top of the nearby mountain, "Sulur". The photo in Fig. 16 presents the expedition team on top of Sulur: In the middle (standing) Adam Paulsen, to his right (sitting) Ivar Jantzen, behind him Harald Moltke, and to the left (sitting) Dan la Cour. The other persons are local (unknown) assistants.

The equipment deployed at the main station comprised standard instruments for meteorological observations of pressure, temperature, humidity and winds and magnetometers for the geomagnetic observations. Furthermore, special instruments were included for the observations of the spectra of auroras both in the visible and in the ultra-violet range, and for measurements of atmospheric electric fields and conductivities.

For the optical observations two spectrometers were used (Paulsen, 1900a, b, c). One spectrometer, shown in Fig. 17, was designed by Otto Toepfer and manufactured by Scheiner in Potsdam. In this instrument the prism and the lenses were made from flint glass. The other spectrometer, designed by Mascart and manufactured by Pellin, was equipped with a prism of Icelandic spar and lenses of quartz glass in order

Figure 16. Iceland Expedition team at the top of Sulur mountain (Photo, DMI).

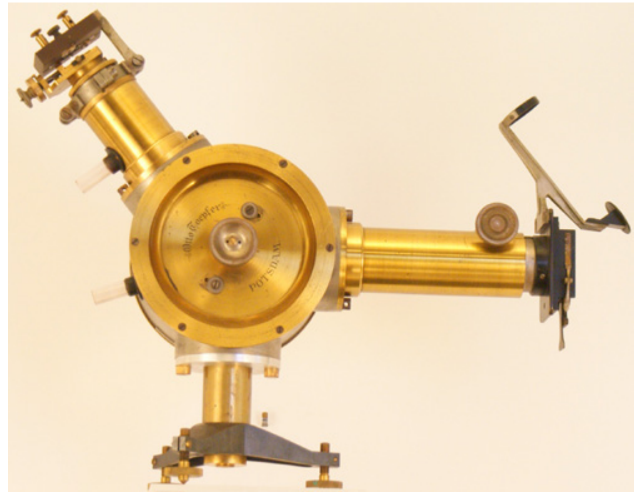

Figure 17. Toepfer spectrometer with mount for calibration light sources at the entrance (left) and sighting means mounted at the rear part (right) (Photo, DMI).

to improve the performance in the ultra-violet wavelength range. For the calibration of the spectrometers small Geissler discharge tubes manufactured by Frantz Müller, Bonn, filled with pure oxygen and nitrogen, respectively, were included along with electrical lamps with filaments of aluminium and copper. These light sources could be mounted in front of the spectrometers to produce reference spectral lines on the photographic strips mounted at the rear of the instrument. The tilt of the prism and the focal length were adjustable to adopt for the different wavelength ranges. A gunners sighting means was mounted at the rear of the instrument to allow an accurate aiming towards the auroras. The spectrometer observations were supervised by Dan la Cour.

For the geo-electrical observations two instruments were included. Both were based on the use of an "Exner" electrometer constructed by Franz Exner (1849–1926). The first one used the principle for measurements of atmospheric electricity devised by the French scientist Gouy. It used an electrode formed by a thin metal disk, 13 cm in diameter, with its top covered by filter paper powdered with a radioactive substance emitting alpha rays (Becquerel radiation) to improve air conductivity in the vicinity of the electrode. The powder was supplied by Pierre Curie (France). The disk was mounted on a ring of copper, which, in turn, was connected to the electrometer. For the observations the device could be mounted at the end of a rod and elevated to a convenient height from the top of the roof. Out of 53 days of electric field measurements only a dozen could be used. On the other days the observations were hampered either by bad weather or by snow drift.

The other geo-electric instrument was devised by the German scientists Julius Elster (1854–1920) and Hans Geitel (1855–1923) (Elster and Geitel, 1899). It used an elongated metallic cylinder mounted at the top of a well isolated modified Exner electrometer. At the start of the measurement, the electrometer was charged from either the positive or the negative electrode of a pile of galvanic elements. Then the relaxation of the electrometer deflection was monitored in order to determine the time constant for the discharging of the cylinder. The time constant is related to the atmospheric conductivity, which was assumed to be proportional to the concentration of ions of the proper polarity in the air surrounding the cylinder. From similar measurements in the European Alpine mountains, Elster and Geitel reported similar time constants for discharging of positive and negative potentials. For the measurements made in Akureyri, both from the base station "Aurora" and from the small shelter located at the top of Sulur, there was a marked difference with consistently larger time constants for discharging the negatively charged compared to positively charged electrometer. Paulsen (1900c, p. 14) concluded that the air close to ground in Iceland is richer on positive ions than air in more southerly regions.

In spite of the sunspot minimum period, the auroral activity in Iceland during the winter 1899–1900 was quite high and the expedition observed numerous large and bright auroral events. The results from spectroscopic observations were reported promptly during the spring of 1900 in two letters to the Royal Academy (Paulsen, 1900a, b). In the preliminary report from March 1900, Paulsen (1900a) reports on having observed 22 lines in the ultra-violet wavelength range not earlier found in the auroral spectra reported, among others, by the French scientist Angot in 1895 (Angot, 1895). A more comprehensive report (Paulsen, 1900c) was issued to the International Congress on Physics assembled in Paris under the auspices of the "Societé francaise de Physique".

In the start of the data processing, the photographic strips used in the spectrographs were visually scanned by using magnifying glasses. Later an ocular mounted on an adjustable micrometer slider was used for the scaling of the recorded lines for precise detection of wavelengths in the auroral spectra. A complete list of observed emission lines is provided in the table published by Paulsen (1900c). The auroral spectral lines were compared to reference lines generated by the calibration light sources and to the lines reported by Angot (1895). There was good agreement between many of the auroral ultra-violet lines and the reference lines produced by the discharges in nitrogen and oxygen gases. An example is displayed in Fig. 18 (from Paulsen, 1906).

In his report to the International Congress, Paulsen (1900c) also reports on the results from the electric and magnetic observations made during the expedition to Iceland. The observations of atmospheric electric field indicate within the observational interval from 08 in the morning until 02 after midnight a regular daily variation with the field increasing from 08 am until 1 or 2 p.m. and then decaying until 02 a.m. Paulsen (1900c) is more inconclusive concerning the relations between auroras and the electric field. He mentions the occurrences of small positive perturbations in the electric potentials during strong overhead auroras.

Further, Paulsen (1900c) reports to the Congress that the effects of the auroras on the geomagnetic field, generally, were fairly small. During quiet auroral arcs there were hardly any notable effects seen on the magnetic instruments. The largest perturbations in the declination were seen during active moving auroras, which also produced many distinct lines in the recorded spectra. However, the deflections observed during the winter 1899–1900 never exceeded 3 degrees even during the greatest auroras, which could be compared to deflections of 10 to 11 degrees observed during strong auroral activity in Godthaab during the Polar Year expedition 1882–1883.

The expedition also tried to estimate the heights of auroras in a simple way. From two not too distant locations they monitored the position of the auroral arcs or bands relative to selected stars. When at one of the locations the star was seen just at the edge of the aurora, the observer here would give a signal to the other observer who would then from his location observe the angular difference between the lines of sight to the selected star and to the lower border of the aurora in that direction. The results were consistently several hundreds of km, usually between 300 and 400 km, and thus, in

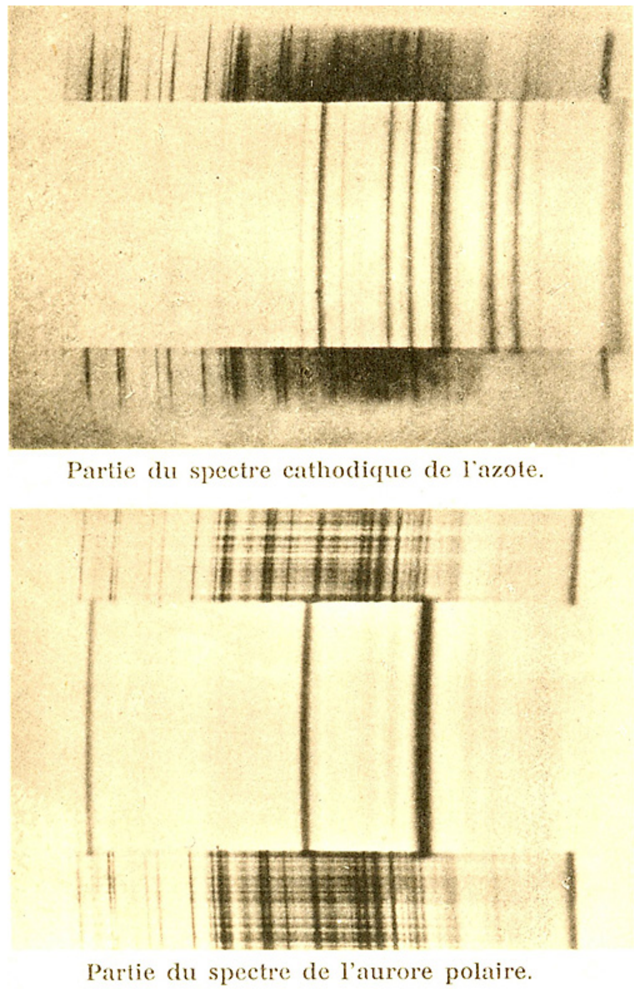

Figure 18. Spectra from Nitrogen gas (top) and from Aurora (bottom). Inserts are magnified sections (Paulsen, 1906).

Paulsen's view, they were rather disappointing. No cases of "local auroras" were observed.

In April 1900 the steamship "Botnia" came again to Akureyri and the expedition team returned to Copenhagen. The most important scientific result was no doubt the photographic recordings of auroral spectra. However, a perhaps even more remarkable outcome from the wintering expedition was a series of brilliant paintings of auroral displays made by Harald Moltke. In order to reproduce the auroras correctly Moltke in the faint light during night watches would make sketches of the observed auroras in pencil strokes on a piece of carton and note the time, the shape and colours of the aurora, its orientation, movements, and further possible characteristics. Next morning in the studio he would then paint the observed aurora based on his sketches and notes. These works, altogether 19 beautiful oil paintings from Iceland, are owned and kept by the Danish Meteorological Institute. The displayed photos of the paintings are from Stauning and Henriksen (2008).

In his own words (in English translation) quoted from the book, (Moltke, 1964, pp. 68–74), Moltke describes the challenge he was facing when arriving in Iceland: "Although I had never seen an aurora, I was convinced, that I could teach myself to paint these heavenly phenomena, since I was profoundly interested in clouds and lighting effects in the air, nocturnal in particular. I was very excited to make acquaintance with the polar lights, which I believed should be painted in pastel shades. However, after having seen the first aurora, I realized that it had to be the oil paints that would best reproduce these fantastic phenomena." [*"Skønt jeg aldrig havde set et nordlys, følte jeg mig overbevist om, at jeg kunne lære mig selv at male disse himmelske fænomener, da jeg interesserede mig meget for skyer og luftbelysninger, særlig natlige. Jeg var meget spændt på at gøre bekendtskab med polarlysene, som jeg på forhånd mente, bedst kunne males i pastel. Men efter at have set det første nordlys blev jeg klar over, at det måtte blive olie-farven, som nærmest kunne gengive disse fantastiske fænomener."*].

Harald Moltke was deeply fascinated by the auroras observed from Akureyri: "Auroras are not like anything else on our globe. They are mysterious. They go beyond the human fantasy to the degree that you instinctively resort to expressions such as "supernatural", "divine", "miraculous". Only little by little did I learn to reproduce these hovering, dancing revelations; only little by little did I realize that in all the arbitrariness, there were still laws obeyed even by these wild, intemperate phenomena." [*"Nordlys ligner ikke noget andet på vor klode. De er gådefulde! De overgår i den grad den menneskelige fantasi, at man uvilkårligt tyer til sådanne udtryk som 'overnaturligt', 'guddommeligt', 'mirakuløst'! Først lidt efter lidt lærte jeg at kunne gengive disse svævende, dansende åbenbaringer, først lidt efter lidt lærte jeg, at der i al vilkårligheden var love, som selv disse vilde, ubeherskede fænomener lystrede!"*].

Moltke describes his first attempt to reproduce the auroras in painting as "some confused daubing, which the scientists (and myself first of all) rejected as being completely useless." [*"noget forvirret smøreri, som videnskabsmændene (og jeg selv først og fremmest) kasserede som ganske ubrugelige."*]. However, he gradually improved his technique and succeeded to produce excellent reproductions of a diversity of auroral forms and colours.

"The first fairly successful aurora was a drapery phenomenon observed on 1 September 1899 (Fig. 19) over the hill just behind our house. With a pencil I sketched the shape of the aurora, indicated the stars through which the veil draperies were moving, and memorized carefully the colours of the aurora and the sky. The next day I painted from memory, backed by the sketches and further studies of the landscape, a picture that was applauded by the scientists." [*"Det første nordlys som nogenlunde lykkedes, var et draperifænomen, set 1. september 1899 over bakken lige bag vort hus. Med en blyant kradsede jeg formen af nordlyset op, angav stjernerne, hvorigennem slør-draperierne bevægede sig,*

Figure 19. Aurora over Akureyri on 1 September 1899 at 17:45 h. The first successful painting by Harald Moltke (Photo, DMI).

samt indprentede mig nøje farven på nordlyset og himmelen. Den næste dag malede jeg efter hukommelsen, støttende mig til disse streger og nogle landskabelige studier, et billede, som vandt videnskabsmændenes bifald."]

"The most common shape of the aurora is the forming of draperies. Giant luminous curtains with folds waved by invisible hands and turned to cornet-like formations, now strongly glowing, now fading away to reappear somewhere else." [*"De almindeligste former for nordlys er draperidannelser. Vældige, lysende tæpper med foldekast, som usynlige hænder vifter med og drejer rundt til kræmmerhuslignende formationer, snart lysende stærkt, snart svindende bort for at opstå et andet sted."*] (see example in Fig. 20).

The arcs span from horizon to horizon and are the steadiest of the phenomena. But suddenly bundles of rays congregate within these arcs like piano keys played by invisible hands, back and forth, back and forth, until they all disappear with a twitch." [*"Buerne spænder fra horisont til horisont og er de roligste af fænomenerne. Men pludselig kan der samle sig strålebundter i disse buer, som tangenter, hvorpå usynlige hænder giver sig til at spille, frem og tilbage, frem og tilbage, indtil det hele forsvinder med et ryk! "*].

The task for the artist painter, Harald Moltke, was to illustrate (in colours) the observed auroras but he was also deeply

Figure 20. Auroral display observed over the base station "Aurora" in Akureyri on 13 January 1900, at 20:20 h by Moltke (Photo, DMI).

fascinated by the scientific efforts from the other members of the expedition to detect the emission lines in the auroral spectrum. "The aurora has its own spectrum. When we started our research, only one line was known, the "Aurora line". Among our tasks was the photographic recording of the auroral spectrum in order to detect further lines in addition to the dominant one. For this purpose Dan la Cour had a very expensive instrument, a spectrograph, resting on a concrete pillar erected from a small pile of soil just outside our observatory. He succeeded to make a photograph – of 3 lines, I think – within the ultra-violet part of the spectrum. La Cour showed me a small plate on which the auroral spectrum appeared indistinctly at the right end. In auroral research this was an epoch-making result and science-wise our finest achievement." [*"Nordlyset har sit eget spektrum. Dengang, da vi begyndte vore forskninger, kendte man nærmest kun een linje, nordlyslinjen. Blandt vore opgaver var at fotografere nordlys-spektret og om muligt derigennem finde flere linjer foruden den udprægede. Til dette brug havde Dan la Cour et meget kostbart apparat, en spektograf, hvilende på en cementsokkel, som ragede op af en lille jordhøj, anbragt lige udenfor vort observatorium. Det lykkedes ham også at fotografere - jeg tror tre linjer – i den ultra-violette del af spektret. La Cour viste mig da en lille plade, hvorpå nordlysspektret tegnede sig utydeligt i højre side. Dette var indenfor nordlysforskningen epokegørende og videnskabelig set vort fineste resultat."*]

8 The Danish auroral expedition to Utsjoki 1900–1901

Strongly encouraged by the successful expedition to Iceland, Paulsen organised another auroral expedition sent out from the Danish Meteorological Institute during the winter of 1900–1901 this time to Utsjoki in the northernmost region of Finland. Paulsen was too aged himself to take part in the expedition, which this time was headed by Dan la Cour. Other members of the expedition team were the master of engineering Carl Edvard Thune Middelboe (1875–1924), university student Johannes K. Kofoed (1877–1939), and the artist painter, count Harald Moltke who like la Cour had been in Iceland with the former aurora expedition.

The main purpose of the expedition was to extend the observations made in Iceland to another region and to look for possible differences. The instrumentation brought to Utsjoki was much the same as that used in Akureyri during the past winter season, that is, two spectrometers, electric field and conductivity instruments, magnetometers, and standard meteorological instruments. The expedition took up quarter in a vacant house in Utsjoki named "England" (after its English owner, Mr. Stewart, who had been eaten by a tiger in India) and established a field station "Denmark" close to the church located 5 km south of Utsjoki. Between the two stations a wire telephone line was constructed in order to synchronize observations.

Paulsen reports in a short communiqué (Paulsen, 1901a) on the results from the expedition. The occurrence of auroras was less frequent than seen during the Iceland expedition, but those observed were more intense and colourful. During 7 weeks of observations from 26 December until 14 February the expedition succeeded in observing a further aurora spectral line at 316 nm deep down in the ultra-violet range (Paulsen, 1901b). The electric field measurements were inconclusive while the conductivity measurements demonstrated a regular daily variation only perturbed during unusual windy conditions. The expedition tried to estimate aurora heights and derived altitudes of 60 to 70 km and above.

Like the case with the expedition to Iceland, a most remarkable outcome from the expedition to Finland was a series of aurora paintings made by Harald Moltke. In his own words (Moltke, 1964, pp. 75–83) (in an English translation) he describes their routine activities:

"When we had accommodated ourselves in the small log cabin, we had a very regular life. On certain hours we had to read-off the instruments and make our observations. My time was equally shared between observations at regular times and painting of aurora displays. Here too I was able to reproduce many characteristic phenomena. Generally, the auroras were

Figure 21. Aurora over Utsjoki on 22 February 1901 at 18:35 h by Moltke (Photo, DMI).

sparser here than in Iceland, but on the other hand they were stronger, faster, and more colourful, red and green. When there were auroras and we, therefore, were very busy with the instruments, then the Lapps would surround us, a wondering crowd, laughing and having fun as if it was a theatre performance. Since the auroras were increasing it was decided to prolong our expedition. The last weeks had particularly strong auroras."

[*"Da vi først havde indrettet os i den lille bjælkehytte, førte vi et meget regelmæssigt liv. Til klokkeslet skulle vi aflæse instrumenterne og gøre vore iagttagelser. Min tid var ligeligt fordelt mellem forsøg til bestemte tider og maling af nordlys. Også her fik jeg gengivet mange karakteristiske fænomener. Gennemgående var nordlysene sparsommere her end i Island, men til gengæld var de stærkere, hurtigere og mere farvede, røde og grønne. Var der nordlys, og vi derfor var i fuld aktivitet ved instrumenterne, omringede lapperne os; en undrende skare, som lo og morede sig, som om de var til en teaterforestilling. På grund af nordlysenes stadige tiltagen blev det bestemt, at vor ekspedition skulle forlænges noget. De sidste uger havde særlig stærke nordlys."*] (see example in Fig. 21).

"Director Adam Paulsen who was most pleased with the results, including those of the painter, planned to collect the material in a great publication on the two aurora expeditions where my paintings – or a selection – should be reproduced in colour. But alas! Adam Paulsen died before the dream of his life, the decisive book on auroras, was written." [*"Direktør Adam Paulsen, som var meget tilfreds med resultaterne, også malerens, ville samle stoffet i et større værk om de to nordlysekspeditioner, hvor mine billeder – eller et udvalg – skulle gengives i farver. Men desværre! Adam Paulsen døde, før hans livs store drøm, den afgørende bog om nordlys, blev skrevet."*].

9 End of the Paulsen era in Danish auroral research

After the successful wintering expeditions to Iceland in 1899–1900 and to Finland in 1900–1901, the subsequent analysis of the collected data continued onward to 1906 ending with a review publication (Paulsen, 1906). In this work, Paulsen examines other recent theories for the aurora and expresses several relevant objections. First, discussing the aurora theories published by the Norwegian scientist Kristian Birkeland in 1896 (Birkeland, 1896), Paulsen demonstrates several shortcomings of the theory. At that time Birkeland had already proposed a modified theory in 1901 (Birkeland, 1901). In Paulsen's view, even Birkeland's new theory, which was also based on the guiding of cathode rays emitted from the Sun into the polar atmosphere along lines of force in the Earth's magnetic field, could not possibly explain the diversity of auroral displays and the great temporal and spatial variability in the intensities and shapes of observed auroras.

Similarly the theory issued by the Swedish scientist Arrhenius (1900) was found by Paulsen to be inadequate. According to this theory, negatively charged particles were "chased away" from the Sun by the pressure of the emitted light thereby producing a continuous "rain" of these particles throughout the Universe. At the Earth this rain would produce electrified clouds, which could only be discharged at high latitudes where the lines of force were vertical. Thus the theory failed to allow for auroras at middle and low latitudes. Furthermore, according to Paulsen (1906) the diurnal and seasonal variations would come out in the wrong way.

Finally, Paulsen discusses the theory expressed by the French scientist Nordmann in 1903 (Nordmann, 1903). According to this theory the Sun emits strong hertzian (electromagnetic) radiation, which is absorbed in the atmosphere and, consequently, not observed from the ground. The preferred occurrence of auroras in the Polar Regions is explained by the extended wave path through the atmosphere at high latitudes where the ionising electromagnetic radiation would create an abundance of charges. Paulsen, correctly, concludes that this mechanism would produce two maxima in the daily variation of auroras; one at dawn and another at dusk, whereas there would be a minimum at midnight contrary to observations. Then, coming to his own views, Paulsen (1906) is unclear. He repeats some of his earlier suggestions but has possibly realized at this time that they too have weak points. He makes an issue of the differences between auroras without (Class I) and with (Class II) rayed structure and describes the characteristics and possible effects within the two classes. His fundamental hypothesis concerning the origin of auroras derived from the experiences in Greenland and Iceland is expressed in his words

(Paulsen, 1906, p. 133): "The cause of the polar auroras should be searched for in an immense ionisation and negative electrification of the upper layers of the atmosphere above the region of maximum auroras of a kind such that this change of the air is renewed every day beginning at the limit of the atmosphere." ["*Mes recherches m'ont porté à chercher la cause de l'aurore polaire dans une immense ionisation et électrisation négative des couches supérieures de l'atmosphère au-dessus de la zone de maximum de l'aurore, de sorte que cette altération de l'air se renouvelle chaque jour en commencant aux limites de l'atmosphère.*"]

10 Two decades of abeyance in Danish auroral research and a new start with the second Polar Year

With Paulsen's final publication in 1906 and his death in 1907 a brilliant era for auroral research in Denmark had come to an end (la Cour, 1907; Freuchen, 1907). With the new director of the Danish Meteorological Institute, Carl H. Ryder (1858–1923), the activity in the field of auroras was limited to routine recordings of occurrences of auroras from the various climate stations, in particular from the lightships that were included in the meteorological observational system in 1897. The research in auroral physics and processes remained dormant until Dan B. la Cour took over in 1923 as the next director of the Meteorological Institute and sparked a renewed interest in auroras. Theoretical calculations of the possible heating of the upper atmosphere in the auroral zone as the result of the bombardment by electrons according to the Birkeland-Størmer theories were made by Helge Petersen (1886–1958) and published in 1927. Adam Paulsen is not mentioned in this publication (Petersen, 1927). The calculations indicate that the upper atmospheric temperatures should rise with altitude as the result of the electron bombardment and reach levels above the temperatures in corresponding atmospheric layers outside the auroral zone. This result has later been experimentally verified. In 1931 the analyses were extended to include calculations of the height profile of the intensity of the green line in the auroral spectrum (557.7 nm) from the assumption that the emitted light was the result of absorption in the atmosphere of the precipitated electrons (Petersen, 1931).

In another research effort, which was devoted to studies of the tidal effects in the ionospheric currents, Johannes Egedal (1891–1965) from the geomagnetic division of the Danish Meteorological Institute demonstrated in 1929 that the grouping of auroral heights recorded in Norway by photographic triangulation could be explained as a tidal effect. The observations were made by the Norwegian scientists Lars Vegard and Ole Andreas Krogness and the statistical representation indicated maximum occurrences at two heights, one around 100 km and the other around 106 km. This grouping was explained by Egedal (Egedal, 1927, 1929, 1930, 1937) as height variations related to ebb and flow in the upper atmosphere and ionosphere.

At the end of the 1920s the International Association for Geomagnetism and Atmospheric Electricity started the preparation for the Second International Polar Year. At the Meteorological Congress in Copenhagen in 1929, director Dan la Cour was appointed President for the Polar Year Commission in charge of the planning of activities. The new Polar Year was planned to take place in 1932–1933, that is, at the 50th anniversary of the first Polar Year. An even larger number of polar stations was planned to operate simultaneously and with uniform procedures for observations and recordings. La Cour assisted in the production of a photographic atlas of auroral forms for the International Geodetic and Geophysical Union, which was issued in 1932 (Auroral Atlas, 1932). Furthermore, he wrote a manual for auroral observations and developed a method of recording visual auroral observations by using transparent star maps that could be placed on a light well for standardized plotting of the position of auroras relative to the stars. These means to assist fast and reliable recording of visual observations were made freely available from the Danish Meteorological Institute for use during the Polar Year. Furthermore, based on a grant of $40 000 US from the Rockefeller Foundation, a large number of high quality magnetic instruments (la Cour and Laursen, 1930; la Cour, 1936) were manufactured in the Geomagnetic Division to be distributed to many observatories that could not buy instruments for Polar Year observations from their own funds.

From the Meteorological Institute three Danish Polar Year Expeditions were sent to Greenland. One expedition headed by Johannes Olsen was sent to the new magnetic observatory built in Godhavn in 1925. Another expedition headed by Viggo Laursen (1904–1997) was sent to Thule where it established a temporary geomagnetic observatory for the Polar Year (Laursen, 1943). K. Thiesen was in charge of a third expedition sent to Julianehaab in the Southern part of Greenland. All three expeditions conducted careful observations of geomagnetism, auroras, meteorology, and (in Thule) aerology and radio conditions through the Polar Year. Particular attention was given to the provision of high-quality auroral observations through careful visual observations and comprehensive notes in the journals. In Godhavn and Thule auxiliary distant stations were established in order to derive auroral heights from photographic triangulation.

Dan la Cour, director of the Meteorological Institute and also chair of the Polar Commission, and his colleague Viggo Laursen worked hard to make the huge amount of data collected during the Second Polar Year available to the international scientific community. Magnetograms and observational reports were copied to microfilms that could easily be circulated among scientists. In 1936 la Cour was elected President of the International Union for Geodesy and Geophysics (IUGG), a position he held until his death in 1942. Viggo Laursen continued his work at MI and published in 1950 (Laursen, 1950) a bibliography of the more than 1000 publications resulting from the Second Polar Year. V. Laursen was member of the Executive Committee of IUGG and became its president during 1960–1963.

Much auroral data material was collected from the Danish Second Polar Year Expeditions to Greenland. Unfortunately, most of this material was not analyzed properly but remained in archives. Among the exceptions was the photographic triangulation material from Thule that was shipped to the Auroral Observatory in Tromsø for analysis and height calculations by the Norwegian professor Carl Størmer. In his book from 1955 (Størmer, 1955), these data have been included. For 26 auroras the heights were estimated to be between 81 and 164 km. Also the individual photographs were examined in order to estimate the average orientation of the auroral arcs, which were considered of special interest since Thule is close to the centre of the auroral zone. For a series of 70 auroral arcs the orientation, generally, turned out to be perpendicular to the local magnetic meridian like those observed at lower latitudes. However, the exact locations of the arcs were not published and it is possible that most of the arcs were located well south of Thule, that is, they were not really high polar auroras.

In 1938–1939 a Danish expedition, headed by Ebbe Munck and Eigil Knuth wintering at "Mørkefjord" near Danmarkshavn in Greenland, made coordinated photographic recordings of auroral arcs and bands with a French-Norwegian expedition to the same region. The material was again processed by Størmer (Størmer, 1947). He estimated heights ranging between 90 and 150 km for the lower border of the auroras in agreement with similar results from Norway. The orientations of the arcs were, as in Thule, generally perpendicular to the magnetic meridian.

In Denmark, since 1897, the weather observers at the lightships had been watching for auroras; thus times for their appearance and disappearance were noted in the meteorological journals. This material was analyzed by Johannes Egedal in 1937–1938 (Egedal, 1938). Most of the results were not quite new, but with the comprehensive and uniform data base the conclusions were better substantiated than results from earlier investigations. Egedal's results confirmed the seasonal maxima at equinoxes in the auroral occurrence frequency, the maximum occurrence of auroras one year after sunspot maximum, and also the decrease in auroral occurrences with decreasing latitude from the northernmost to the southernmost lightship.

An original observation was the day-to-day variation in auroras related to the appearance of sunspots. Egedal (1937) noted that the maximum probability for observing auroras came one day after the passage of a big sunspot through the meridian at the Sun oriented towards the Earth. This observation was based on the regular recordings of sunspots, which had been conducted at the Danish Meteorological Institute since 1919 on clear days. An image of the solar surface was projected on to a drawing sheet and the sunspots were carefully marked. This work was continued until the 60s in order to assist the forecasting of auroras and magnetic storms.

During World War II, in 1939–1945, the communications with Greenland were disrupted and the operation of light ships was suspended. Hence auroral observations from this interval are rather sparse. As the War ended the observations of auroras in Greenland and from the lightships were resumed and the visual observations continued until 1969. This material also includes the auroral observations made by the Danish Pearyland Expedition in 1948–1950 to Brønlund Fiord in Northeast Greenland.

From the geomagnetic observatory in Godhavn, founded in 1925 by Dan la Cour, and operated by the Meteorological Institute, the station manager, Knud Lassen (1929*), observed during the years 1952–1956 the occurrences of auroras every evening from sunset until around midnight. During the last two years the auroras were also observed regularly during the early pre-dawn hours. These visual observations were made as frequent and continuous as possible, often extending over several hours without pauses. From the results of the observations published in 1959, Lassen (1959a, b, 1961a) concluded that there existed at this latitude two different kinds of auroras. One type, preferably observed during the evening and night is bright and dynamic. The auroras move from the southern horizon toward the station with many motions and brightly coloured. After around one hour the auroras soften and retreat gradually. During their active display the magnetic field is strongly disturbed. The other main type of auroras is predominantly seen in the morning hours. This type comprises quiet weak auroral arcs observed high in the sky, which are not related to magnetic variations (Lassen, 1961b).

These observations revived the earlier discussions between Tromholt and Paulsen. According to Tromholt's theory (Tromholt, 1882a) the auroras in the morning should have reached their northerly position through a gradual displacement of the auroral zone during the night. Paulsen (e.g., Paulsen, 1993c) had questioned this view. From the new observations Lassen concluded that the morning auroras emerge at latitudes comparable to that of Godhavn (geomag. lat. $\sim 79°$) far north of the auroral zone. Thus, they could not be considered the result of a gradual shift of the auroral zone towards the North. These high-latitude morning auroras are described by Lassen in several publications (e.g., Lassen 1959a, b) where their appearance, position, orientation and relation to magnetic field variations are characterized. Further supported by data from the weather stations in Greenland and from the Brønlund Expedition, Lassen (1959a) concluded that the morning auroras form a special inner auroral zone running parallel with the classical auroral zone formed by the evening and night auroras.

11 The International Geophysical Years 1957–1959

During the International Geophysical Years (IGY) 1957–1958 (extended to 1959) the global net of ground-based auroral observatories was greatly extended and the equipment upgraded. The visual auroral observations made at the Danish light ships and at the weather stations in Greenland were intensified. For auroral observations during the IGY the Danish Meteorological Institute operated four auroral stations in Greenland. They were located in Nord, Godhavn, Kap Tobin, and Julianehåb and equipped with all-sky cameras of the Stoffregen model. The cameras were oriented in the geomagnetic N-S/E-W direction. Photographs of the sky were made at 1-min intervals. For the scaling of the film recordings, the "Stoffregen rules" were applied: in the E- or W-directions auroras lower than 30° elevation were neglected. In the N-S directions auroras below 10° elevation were neglected. Auroras of high elevations between 30° N and 30° S were termed Z- (Zenith) auroras, those between 10° and 30° were termed either N- or S-auroras.

The comprehensive data material obtained from Greenland and from a number of stations in Canada, Alaska and in Antarctica has been analyzed by Lassen and colleagues O. Rud Laursen and Johannes Olsen from the Meteorological Institute and were presented, among other publications, in the thesis work from 1963 (Lassen, 1963) and in Lassen et al. (1964). In addition to the IGY observations, Lassen (1963) also included observations made during the First Polar Year 1882–1983, during the Second Polar Year 1932–1933, and selected observations made during intervals between the international years.

Lassen was particularly interested in the occurrence of auroras at very high latitudes. In order to solve the important question of whether or not these aurora constitute a separate population, he re-analyzed the daily variation in auroral occurrences based on observations made during the First International Polar year. The result is displayed in Fig. 22 where the stations are organized according to their magnetic latitude. For the low-latitude stations (bottom) there is one simple maximum centred in the evening (magnetic time). For the stations very close to the pole (top) the occurrence frequency is small. However, for those at intermediate to high latitudes there are clear additional occurrence maxima in the morning hours.

The IGY years were also the years of the largest recorded maximum in sunspot activity and the auroral occurrence frequencies at lower latitudes, for instance in Denmark, were unusually high. There were reports on the formation of a separate lower-latitude auroral region for the evening and night types of auroras. Combining all available observations from the First Polar year, the IGY years, and the years in between, Lassen (1963) deduced the latitude dependence of the occurrences of evening and night auroras depicted in Fig. 23. Here, both the high-latitude and the low-latitude maxima in addition to the central auroral zone maximum are distinct.

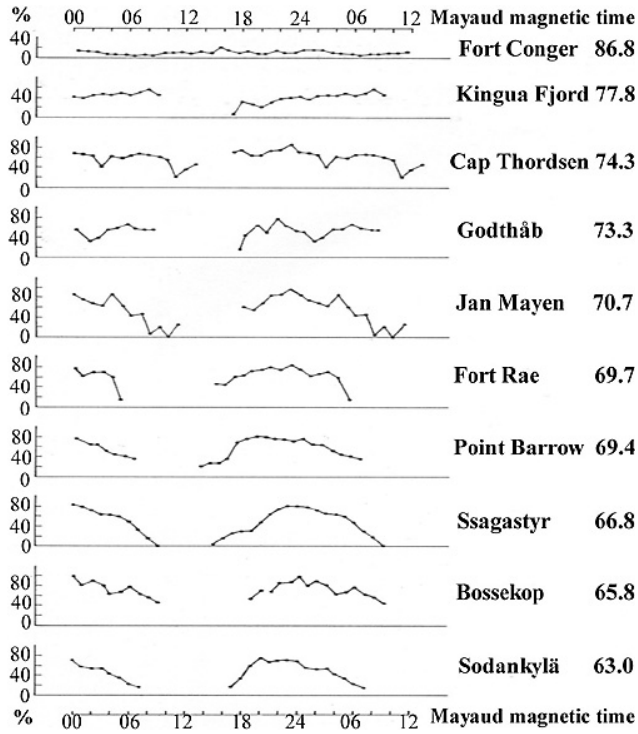

Figure 22. Daily variation in aurora occurrence frequencies 1882–1883 (Lassen, 1963).

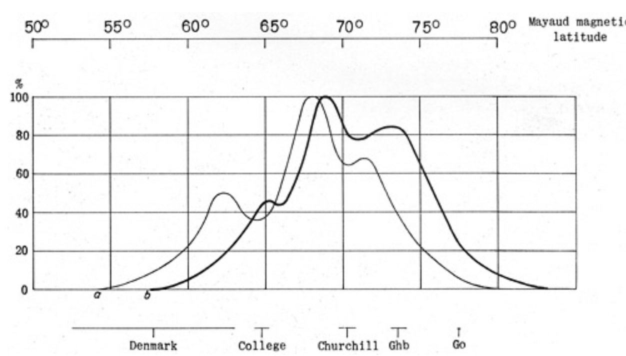

Figure 23. Latitude dependence for night auroras at sunspot maximum **(a)** and minimum **(b)** (Lassen, 1963).

Furthermore, the figure displays the sunspot cycle variation which is a combination of the simple shift in latitude suggested by Tromholt (1882a) and the variation in the relative importance of the low-latitude and high-latitude enhancements suggested by Lassen (1961b, 1963).

Turning to the morning and dayside auroras, many observations suggested the existence of another occurrence maximum in the post-noon hours in addition to the morning maximum in aurora occurrence frequency. The newly developed theories for the interaction of the solar wind with the magnetosphere predicted a tail region of field lines emerging from the dayside but convected tailward to the night side. Due to

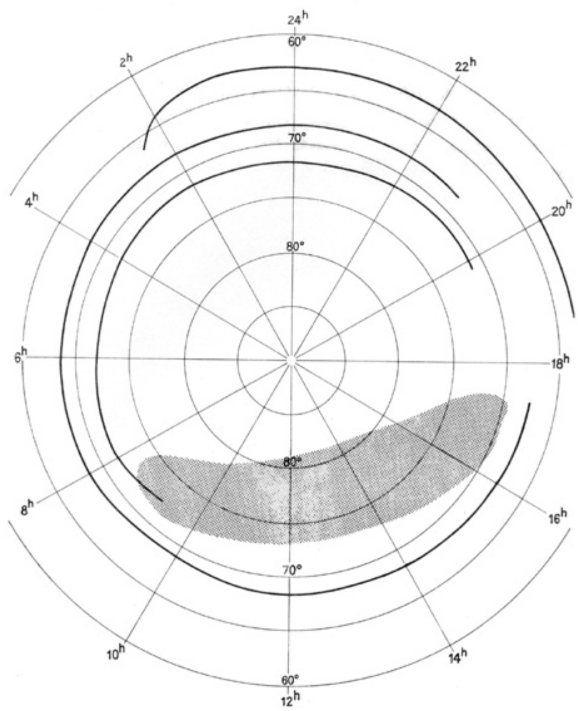

Figure 24. The four auroral regions (Lassen, 1963).

the "frictional interaction" suggested by the Canadian scientists Axford and Hines (1961) the plasma in the tail region would be in a turbulent state creating an "area of confusion" at high latitudes on the dayside at the feet of the connecting field lines. Lassen (1963) now suggested a division of the auroral occurrences into four regions:

1. "normal" auroral zone centred at 68–69° magnetic latitude
2. high-latitude auroral zone centred at 71–72° latitude
3. low-latitude auroral zone centred at 63–64° latitude
4. very high-latitude dayside auroral region within the "area of confusion".

These regions are illustrated in the polar diagram of magnetic latitude and magnetic time in Fig. 24 from Lassen (1963). With some small modifications they agree quite well with present-days concepts for auroral occurrences. Based on the comprehensive amount of data from polar auroral observatories, Lassen (1963) depicted the occurrence frequencies by iso-aurora contours (isochasm) in polar diagrams of magnetic latitude-local time.

In the representation displayed in Fig. 25, Lassen (1963) is very close to the conclusion that the region of maximum auroral occurrences forms an oval fixed in space beneath which the Earth is rotating. The minimum latitude for the oval is located shortly before midnight while the maximum auroral oval latitude is located at around noon. This concept is very close to the pattern for the daily variation in the occurrences of auroras suggested by Tromholt (1882a).

The concept of a continuous oval with adjoining occurrences of auroras was published by the Russian scientist Yasha I. Feldstein (Feldstein, 1963) in the same year and the auroral oval is now also known as "Feldstein's Oval".

12 Further Danish auroral research in the IQSY years 1964–1965 and thereafter

The IGY took place during an unusually strong sunspot maximum. The results in many fields, therefore, could not be considered generally representative: Thus there was interest in repeating observations during the approaching solar minimum in order to span all solar activity phases and the "International Quiet Sun Year" (IQSY) epoch was agreed to take place during 1964–1965. The Danish Meteorological Institute resumed the photographic auroral recordings in Greenland. The array of stations was extended to comprise Thule, Godhavn, Sukkertoppen, Narsarsuaq at the West coast and Nord, Kap Tobin at the East coast of Greenland. Further visual auroral observations were made from the observatories, among others, from Thule by Christian Danielsen (1932*). The IQSY observations have been processed and have provided the basis for further publications from the Danish Meteorological Institute (Danielsen, 1969; Lassen, 1967, 1969, 1970a, b; Lassen and Rud Laursen, 1968a, b).

The array of auroral stations in Greenland was further extended during the 1970s such that their overlapping field-of-view extended over Greenland from the auroral zone in the South up to and including the magnetic pole in the North. The auroral observations were augmented by the extensive ground-based magnetic and ionospheric observations in Greenland conducted by different divisions at the Danish Meteorological Institute. Further scientific analyses of the auroral observations have also included the use of rocket and satellite data on the particle radiation considered responsible for the activations of auroras. During the 1980s excellent satellite-based auroral observations have gradually reduced the need for ground-based observations of this kind. The demanding and costly auroral photographic recordings were gradually reduced and finally all stopped in the early 1990s.

However, the geomagnetic and ionospheric observations conducted in Greenland and other places in the Arctic by the Danish Meteorological Institute (now DMI) were continued and extended. In addition to auroral research, the DMI research in the fields of electric and magnetic properties of the ionosphere and magnetosphere, their coupling to the solar wind, and the relations to solar activity reached in these years an internationally highly acknowledged level. Thus, the continued geophysical activities at DMI were an essential part of the scientific background for the first Danish satellite "Ørsted".

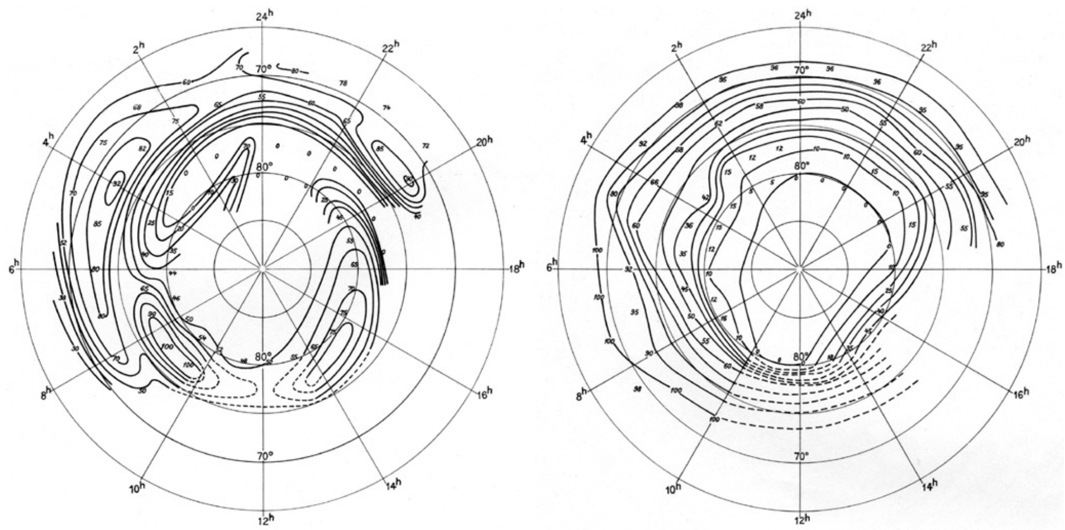

Figure 25. Iso-auroral contours for sunspot minimum (left) and maximum (right). Note that local noon is downward (Lassen, 1963).

The Ørsted satellite, named after the Danish Scientist H. C. Ørsted, and equipped with instruments for precise measurements of the Earth's magnetic field and the radiation in Space, was proposed in 1991 by a group of scientists comprising Fritz Primdahl, John Jørgensen, Torben Risbo and Peter Stauning. With Eigil Friis-Christensen as scientific project leader, strongly supported by industry with Jens Langeland Knudsen heading a group of Danish companies, and with additional support from the international space agencies, NASA, ESA, CNES, and DLR, the satellite was built in Denmark and on 23 February 1999 launched into a low polar orbit. The satellite is still (in 2010) in operation. Its tenth anniversary was celebrated in February 2009 (Fig. 26).

Figure 26. Celebration of Ørsted's 10 years in Space on 23 February 2009.

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