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Sophus Peter Tromholt: an outstanding pioneer in auroral research

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Abstract. The Danish school teacher Sophus Peter Tromholt (1851–1896) was self-taught in physics, astronomy, and auroral sciences. Still, he was one of the brightest auroral researchers of the 19th century. He was the first scientist ever to organize and analyse correlated auroral observations over a wide area (entire Scandinavia) moving away from incomplete localized observations. Tromholt documented the relation between auroras and sunspots and demonstrated the daily, seasonal and solar cycle-related variations in high-latitude auroral occurrence frequencies. Thus, Tromholt was the first ever to deduce from auroral observations the variations associated with what is now known as the auroral oval termed so by Khorosheva (1962) and Feldstein (1963) more than 80 yr later. He made reliable and accurate estimates of the heights of auroras several decades before this important issue was finally settled through Størmer's brilliant photographic technique. In addition to his three major scientific works (Tromholt, 1880a, 1882a, and 1885a), he wrote numerous short science notes and made huge efforts to collect historical auroral observations (Tromholt, 1898). Furthermore, Tromholt wrote a large number of popular science articles in newspapers and journals and made lecture tours all over Scandinavia and Germany, contributing to enhance the public educational level and awareness. He devoted most of his life to auroral research but as a self-taught scientist, he received little acclaim within the contemporary academic scientific society. With his non-academic background, trained at a college of education – not a university – he was never offered a position at a university or a research institution. However, Sophus Tromholt was an outstanding pioneer in auroral research.

1 Introduction

Sophus Peter Tromholt (1851–1896) was born on 2 June 1851 in Husum, Schleswig. His parents were customs officer Johan Peter Tromholdt, (1821–1912) from Copenhagen, and Ane Cæcilie Keller, born 1830 in Ribe in Jutland. Sophus was the oldest among their 5 children. In 1859 the family moved to Oldenburg in Holsten. At that time Schleswig and Holsten were part of the Danish Kingdom but had a special status as Duchies under the Danish Crown. In 1863, the year before the second Schleswig war between Denmark and Germany, the Tromholt family moved to Randers further north in Jutland. In 1868 Sophus Tromholt started his training at *Blaagaard Seminarium* (College of Education) in Copenhagen. He finished the education to become a school teacher in 1871.

Already in 1870, at just 19 yr of age, he started to submit detailed descriptions of his auroral observations to the Copenhagen newspaper *Dags-Telegrafen*. Upon his graduation in 1871, Tromholt was employed for a year as a private school teacher for the family at the estate *Svanholmsminde* close to Aalborg in northern Jutland. Living at the countryside, Tromholt had ample opportunities to observe auroras during the dark nights of the winter 1872/73. These observations were published in *Wochenschrift für Astronomie, Meteorologie und Geographie* as the first scientific contribution from the then 22 yr old Sophus Tromholt.

From 1873 Tromholt was a teacher at the public school, *Borgerskolen*, in Horsens in mid-Jutland until his employment in 1875 at *Den Tankske Skole* (The Tank's School) in Bergen, Norway, where he worked until 1882. During the years of teaching Tromholt wrote several widely recognized textbooks in mathematics, geography and astronomy.

During his years as a teacher in Bergen, Tromholt organized coordinated observations of auroras all over Scandinavia. The first campaign took place during the winter

1878/79. Tromholt wrote to around 600 persons, vicars, sea-captains, weather observers and even directors of meteorological institutes, all over Scandinavia with a request for observing and reporting occurrences of auroras. The observations were analyzed and in 1880 reported to the Norwegian Academy of Science and Letters in Christiania (Tromholt, 1880a).

At this time, possibly as a consequence of his enthusiastic approach to the Danish Meteorological Institute, he was asked by its director, Niels H. C. Hoffmeyer (1835–1884), to analyze series of auroral observations from Greenland and Iceland, notably those made by Samuel Kleinschmidt (1814–1886) from Godthaab (now: Nuuk) in Greenland. This material was the basis for his famous work: *Sur les périodes de l'aurore boréale* (On the periods of the aurora) published in *Meteorologisk Aarbog* (Meteorological Yearly Report) for 1880 issued by the Danish Meteorological Institute in 1882 and in a separate reprint (Tromholt, 1882a). This activity was reported quite extensively by Stauning (2011) and shall here be dealt with cursorily, only.

In addition to continuing efforts to organize campaigns with coordinated auroral observations all over Scandinavia during 1879/80 and 1880/81 including letters to more than 1000 potential observers, Tromholt also started to consider his involvement in the First International Polar Year to be held during 1882/83. He was aware of the Norwegian Polar Year Observatory located in Bossekop in northern Norway and managed by Axel S. Steen from the Norwegian Meteorological Institute in Christiania (now: Oslo). Tromholt decided to conduct his own Polar Year expedition to the small Sami settlement Kautokeino, around 100 km south of Bossekop.

The outcome of this expedition is reported in the book *Under the Rays of the Aurora Borealis* from 1885 (Tromholt, 1885a). In addition to an extensive chapter on auroras with brilliant auroral observations and analyses, the book is also renowned for its descriptions of the Sami people and their way of life and, not least, for the original and respectful photos of Sami individuals, which are now considered a treasure for ethnographic studies.

In spite of his ingenious scientific works and comprehensive efforts in outreach activities in many natural science fields, Tromholt was not really accepted in the academic scientific society in Scandinavia. His analyses and conclusions were heavily criticized, among others, by Adam F. W. Paulsen (1833–1907), leader of the Danish Polar Year Expedition to Godthaab in 1882/83, and since 1884 director of the Danish Meteorological Institute. Thus, Tromholt was never rewarded a permanent position and had to provide for himself and his wife since 1889, Maria Margaretha Jess (1866–1948), by the modest income from popular talks, newspaper articles, and books. Since his marriage Tromholt resided in various places in Germany. On several occasions he tried to resume auroral research and publication activities but was disappointed by the lack of interest in his work. In 1896 he died at a sanatorium in Thüringen, Germany. His huge collection of past auroral observations in Norway was handed by his wife to J. Fr. Schroeter, Christiania, and published posthumous in 1898–2001 (Tromholt, 1898).

2 Sophus Tromholt's budding interest in auroras

In 1859 the Tromholt family, now extended by three sisters to Sophus, were living in Oldenburg in the Danish Duchy, Holstein (now part of Germany). At this time in the rising part of solar cycle #10, the Sun was particularly active. Large clusters of sunspots scarred the rotating face of the Sun and spurred occasional outbursts, which in turn generated large geomagnetic storms and impressive auroral displays also at temperate latitudes. The interest in auroras increased and inspired to numerous publications on their appearance and characteristics. Professor Chr. Hansteen from Christiania University, widely renowned for his pioneering contributions to geomagnetic and auroral research (Hansteen, 1819, 1827), published in May 1859 an article on auroras in the scientific journal *Wochenschrift für Astronomie, Meteorologie und Geographie*, where he mentions sounds associated with auroras, which were heard in Iceland by his nephew, in one case even through closed windows (Hansteen, 1859). Auroral sound is an issue still debated (e.g. Silverman, 1973).

At this time, in August 1859, solar activity culminated as the sunspots formed huge clusters, which were observed in many places. In "The Times" for 27 August a correspondent notes that these spots (or holes as he terms them), which could have a diameter of 8 times the diameter of the Earth, would have an immediate influence on the temperature in our atmosphere since they, according to his experience, were always accompanied by unusually warm weather. In the middle of the day on 27 August 1859, the first of a series of large solar explosions occurred. One and a half day later, during the night between 28 and 29 August, violent and colourful auroras accompanied by magnetic and electric disturbances occurred in many places. In Europe the auroras were observed in Copenhagen, London, Paris, Vienna, and even in Rome and Athens (Green and Boardsen, 2006).

On 1 September 1859, at 11:18 Greenwich Mean Time, for the first time ever, a solar flare in progress was observed. The observation was made by the British astronomer, Robert C. Carrington, who published his unique experience in the *Royal Astronomical Society* under the title: *Description of a singular appearance seen in the Sun on 1 September 1859* (Carrington, 1860). Already 17.6 h later a violent magnetic storm, later named the "Carrington storm", hit the Earth and sparked beautiful auroras that were seen almost all the way to equator (Cliver and Svalgaard, 2005; Green and Boardsen, 2006; Clauer and Siscoe, 2006).

The bright auroral displays were widely reported in Danish newspapers. Whether father Johan Tromholdt and son, Sophus Tromholt, have themselves observed these auroras is not known. However, Hansteen's report on auroral sounds and the recent brilliant auroras inspired Johan Tromholt to submit a short article on *Geräusch bei Nordlicht-Erscheinungen* (Noise at auroral displays) to *Wochenschrift f. Astron. Met. Geo.* (Tromholdt, 1860). He reports having heard noise accompanying three particularly strong auroral events among "*the many auroras, which I have observed in Copenhagen and later in Jutland and the duchies Schleswig and Holstein*".

The fact that Johan Peter Tromholt, a customs clerk, would write an article to a scientific journal is quite remarkable and indicates a strong interest in auroras. Furthermore, he mentions to have seen many auroras from Holstein (i.e. Oldenburg) where the family lived while Sophus Tromholt grew from 8 to 12 yr of age – an important span of years in the development of a young boy's interests and perspective in his life. Another important feature is the father's strong belief that audible sounds could accompany the bright auroras. Sophus Tromholt never himself heard auroral sounds even during the dark and extremely quiet winter nights in Kautokeino. However, through his life, he was deeply fascinated by the possibility that aurora might generate noise and reported faithfully on observations made by other persons (including his father's) although with increasing scepticism in the later years.

In Randers, Sophus Tromholt finished school with excellent marks in natural sciences and in general manners. Then, in 1868, he moved to Copenhagen and started training at the *Blaagaard Seminarium* (Blaagaard College of Education) to become a school teacher in mathematics and natural sciences. He was profoundly interested in astronomy and was fortunate to have the famous astronomer Heinrich Louis d'Arrest (1822–1875) among his teachers. d'Arrest, a German astronomer, was appointed head of the new Copenhagen Astronomical Observatory upon its start in 1861. He is renowned for having predicted the discovery of planet Neptune and several comets of which one is named after him. There is no doubt that d'Arrest has sparked Sophus Tromholt's genuine interest in astronomy. As d'Arrest died in 1875 Tromholt wrote his obituary and had it printed in several German journals (Tromholt, 1875a, b).

In the fall and winter of 1870, 11 yr after the great Carrington geomagnetic storm, the Sun was again quite active and caused a number of auroral events over Denmark. Tromholt was an eager astronomical observer and quite familiar with the starry sky. From the outskirts of Copenhagen he observed many of these auroral events and his fascination of these unusual features in the sky made him write several enthusiastic reports to be published by the Danish newspaper, *Dags-Telegrafen* (Tromholt, 1870a, b, c, 1871). From his detailed and colourful descriptions of the auroras it is clear that he was deeply fascinated by these phenomena, but it is also evident that he had already given them many thoughts. His descriptions are comprehensive and accurate.

Like most others at that time he assumed that auroras were meteorological-electrical phenomena on line with lightenings and with optical properties like rainbows or halos. Tromholt was aware of the crude relation between auroras and the occurrence of sunspots (the direct link was first settled in the 20th century). In his reports to *Dags-Telegrafen* he rejects the widely held opinion that auroras were caused by reflections from ice crystals in the atmosphere. He is more uncertain about auroral sounds and refers Hansteen's (1859) statement in favour of such sounds as well as the statement by Erslev, who in the chapter on polar light in his book *Jordkloden og Mennesket* (Globe Earth and mankind) from 1860 (Erslev, 1860, p. 58) claims that we may hear such sounds because we expect to hear them. It is surprising that a young man, only 19-yr of age and still in training, involve himself in publishing scientific arguments, but his early notes on auroras provide an apt illustration of Sophus Tromholt's self-confidence and enthusiasm.

3 Auroral observations from Svanholmsminde

Having graduated from the *Blaagaard College of Education* in 1871, Tromholt was employed as a private teacher at the estate *Svanholmsminde* close to Aalborg in northern Jutland. Tromholt was housed in a small cottage a little away from the main building, and here he started systematic observations of auroras. Based on his intense auroral observations Tromholt wrote his first scientific article to be published in *Wochenschrift f. Astron. Met. Geo.* (Tromholt, 1873a) and also printed in a separate version with illustrations under the title: *Nordlichter in den Monaten December und Januar beobachtet zu Svanholmsminde* (Auroras observed from Svanholmsminde during the months of December and January) issued in 1873 (Tromholt, 1873a).

It is evident from this publication that Tromholt systematically watched for auroras almost every single night during December 1872 and January 1873. Most of the publication is used for detailed descriptions of the observations with an abundance of references of the positions of the auroras relative to the star constellations and with very specific reports on the shapes and colours of the observed auroras. He notes for the auroral observations on 25 January 1873, that the poleward orientation of cirrus clouds seen in the afternoon would forecast an increased magnetic activity and enhanced probability for the occurrence of auroras later in the evening. The cirrus cloud formation might just be an indication of fair weather conditions (which are also needed for auroral observations), but it is noteworthy that Tromholt links magnetic activity and auroras.

Further reflections were made over the orientation of the auroral arcs particularly for the multiple displays on 25 January 1873. Two of Tromholt's sketches of the auroras are displayed in Fig. 2. He observed the direction either to the highest point of the arcs and their associated "dark segments"

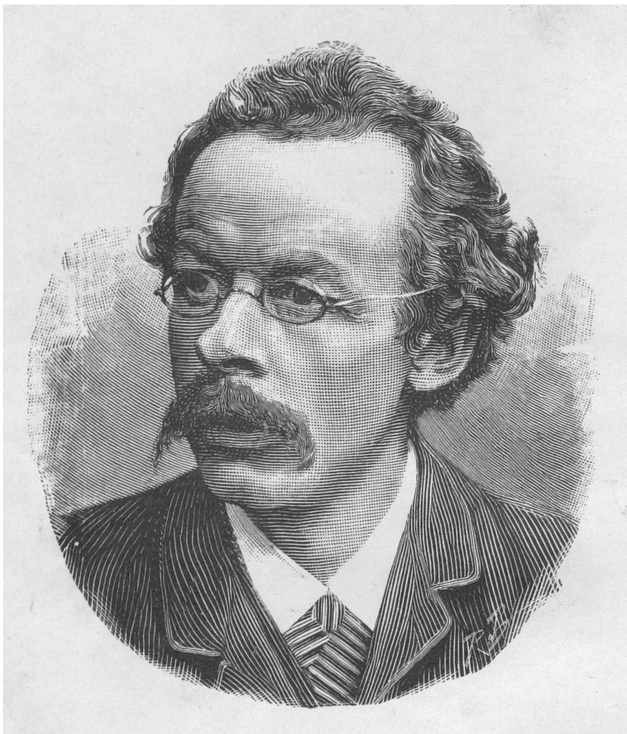

Figure 1. Sophus Tromholt (from Tromholt, 1889).

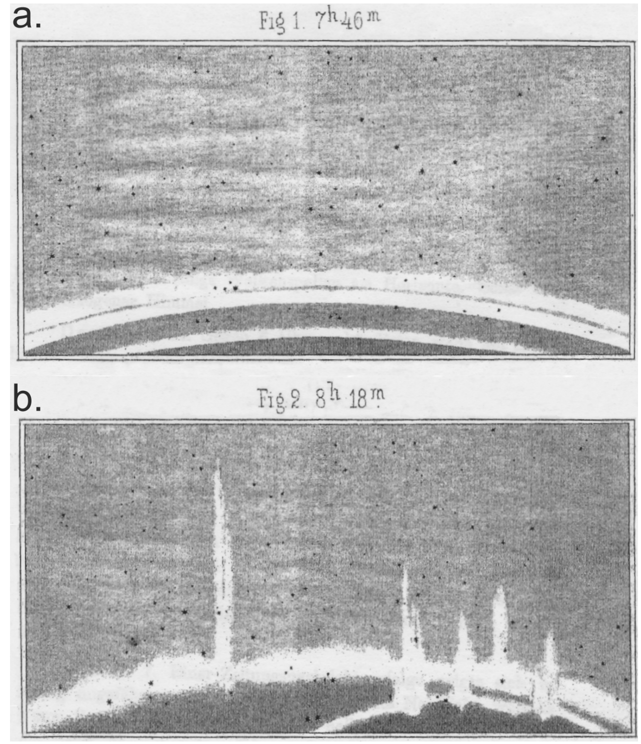

Figure 2. Sketches of auroras seen 25 January 1873, from Svanholmsminde (from Tromholt, 1873a).

(the dark space below the arc) or to the midpoint between the foot points of fully extended arcs. For this day he reported 11 directions between extremes of 9° and 27° west of north with an average value of 18°. He notes in the article that the local magnetic declination is 15°.

It is worth noting that Tromholt at this time also had an eye for the geographical extent of the auroras. He notes along with his own reported observations whether corresponding auroras were observed elsewhere from places like Randers further south in Jutland and Dallund and Assens on Funen around 200 km away from Svanholmsminde. Although this article might be considered premature in comparison with Tromholt's later works, it still indicates his outstanding observational skills and vigorous approach to settle the auroral mysteries.

4 School teacher in Bergen, Norway

After *Svanholmsminde*, Sophus Tromholt was in 1873 employed as a teacher in natural sciences at the public school, *Borgerskolen*, in Horsens in mid-Jutland. He was busy with many further tasks; he gave public talks, wrote various small articles in newspapers and even composed a few music pieces. He also kept watching for auroras and further astronomical phenomena (Tromholt, 1873b, 1874a, b).

Then, in 1875 he moved to Norway and was employed at *Den Tankske Skole* (The Tank's School) in Bergen, Norway, where he worked until 1882. Why Sophus Tromholt took a position in Bergen is not known. However, it is quite possible that his profound interest in auroras made him move to Norway to be closer to the "home of the auroras". In addition, Bergen was a centre for much activity in natural sciences.

During the years of teaching Tromholt, in addition to an abundance of popular science articles (Tromholt, 1877a, b, 1878c, d, e, 1879c, d, e, f), wrote several widely recognized textbooks in mathematics, geography, and astronomy. The first was a textbook in mathematics with the title: *200 Regneopgaver. Til brug for Middelskolens øverste Klasser* (200 arithmetic problems. For the elder classes of the public school) issued in Bergen in 1878 (Tromholt, 1878a). Another was *Lærebog i Geometri for Middelskoler* (Textbook on Geometry for public schools) issued in 1879 (Tromholt, 1879b). In the preface to the book he wrote (in translation): "*The purpose of the book is not to teach pupils to do calculations but to teach them to think*". The most renowned book was *Geografiske Talstørrelser i Billeder* (Pictorial illustrations of geographical quantities) issued in 1878 (Tromholt, 1878b). For this book he was in 1878 awarded a bronze medal at the *Exposition Mondiale* (World Exposition) held in Paris, and in 1879 rewarded a silver medal by the French *Academie Nationale* (National Academy) in Paris. The Academy even offered him a membership, which, however, he was quite reluctant to accept not knowing whether it was "*a shame or an* *honour to be a member*" (letter to Frederik Wallem, Bergen 17 June 1878).

However, the auroras were his prime interest and he frequently cursed the poor weather in Bergen where heavy rain and overcast would often deteriorate or completely prevent his observations. Now he also realized that localized observations gave limited possibilities for analyzing essential properties of the auroras like the combined temporal and geographical developments of auroras and their occurrence distributions. Resolving the important question regarding the height of the aurora was an issue of particular importance. Carl Frederik Fearnley, professor at the Norwegian University in Christiania and director of the Astronomical Observatory, published in 1859 his results from 21 estimates of the height of the lower border of auroras, which gave a mean value of 207 km (Fearnley, 1859). The method was based on observations of auroras from a single position using the concept of a continuous auroral ring proposed by Hansteen (1827). A quite good result considering that the height of the lower border of auroral curtains is around 100–150 km in most cases.

Now, in 1877, Tromholt fostered the idea that a network of observers might contribute to give definite answers to these fundamental questions. As a start he wrote on 23 October 1877 to professor Henrik Mohn, director of the Meteorological Institute in Christiania, with a suggestion to conduct coordinated auroral observations from Bergen and Christiania. In his letter, Tromholt mentioned his previous auroral observations published in *Wochenschrift f. Astron. Met. Geo.* and complained about the lack of interest in auroral studies with the provocative question (in translation): "*Is nothing done in Norway for the aurora?*"

On the same issue Tromholt wrote again to professor Mohn on 17 September 1878 with a similar, slightly offending formulation (in translation): "*Isn't there a single person interested in auroras at the Meteorological Institute? The baseline Bergen-Christiania could, I believe, provide insight into the parallax of the aurora.*" (i.e. provide estimates of their height).

Sophus Tromholt then decided to pursue another line. In the introduction to the report (Tromholt, 1880a) he wrote (in translation): "*To realize the nature of the aurora, little could be done by individual efforts; the goal could only be achieved through collaborative work. With this conviction and with a sincere wish for being able to contribute to progress in this field, I took in November 1878 the decision to attempt to provide, on a larger scale than ever before, corresponding auroral observations over a large region.*"

Further in the introduction he described his own observational scheme and the means used to assist him in the precise observations. One was a kind of theodolite that could provide sighting of azimuth and elevation to selected points in the auroral displays. Another was a light box with a glass top that could be used with sheets of pre-prepared horizon contours of the ambient mountains to make drawings of observed auroras. An important tool was also a precision clock to provide good timing of the observations. He adjusted his clock every day at the local telegraph station where they kept a precise timing. Tromholt was well aware that such means, and the observational skills to use them, would be absent in most of the other observing places. However, he envisaged a long-term project and hoped to gradually train the observers as their interests in auroras were aroused and their skills developed through practising (Tromholt, 1881a).

In consequence of his decision, he sent out letters to vicarages, to lighthouses, and to sea-captains all over Norway with enclosed forms and a request to record all observed auroras through the winter 1878/79. Of the 600 forms Tromholt sent out, close to 100 were returned with recorded observations. Similarly, Tromholt contacted the directors of the Nordic meteorological institutes. In addition to professor Mohn in Christiania, he contacted professor Rubenson in Stockholm, Professor Hildebrandson in Uppsala and Captain Hoffmeyer in Copenhagen asking for copies of the notes on auroras made in the daily reports from the weather stations. For the winter 1878/79 Tromholt received notes on observations of auroras from 132 stations in the three Nordic countries for a total of 154 nights. Altogether he collected 839 reports on auroras from September 1878 to April 1879.

Now, Tromholt was facing the difficult task of analyzing the large but rather inhomogeneous material. For his own observations he had made a strict scheme. On days with clear sky he went out to look for auroras every quarter of the hours from sunset to midnight. He kept on even in the absence of any indication of auroras from the opinion that an observation of no aurora could be as important for his analyses of their localized behaviour as an observation of auroras. In case of the occurrence of auroras he would observe the sky continuously and make notes of any possible change at least every 5 min. At other stations the reporting was generally much sparser. At times just a note was made that auroras were seen in the evening without any indication of time or other characteristics of the observation.

Tromholt published the observations along with his remarks in the report *Iagttagelser over Nordlys anstillede i Norge, Sverige og Danmark i September 1878–April 1879* (Observations of auroras made in Norway, Sweden and Denmark during September 1878–April 1879). The report was presented to the Academy of Sciences in Christiania (by professor Mohn) in 1880 and issued as a special reprint the same year (Tromholt, 1880a). Here, Tromholt reports on the individual observations day by day. The differences between the amount and the quality of his own observations mostly from Bergen and other observations are quite obvious.

In an example (p. 35–48) from 1 December 1878, Tromholt starts his report this way: "*Bergen. A magnificent aurora, the strongest I have seen in the past 6–7 years. Three times it culminated in matchless beauty*". Then follows 320 lines (!) with a detailed description of the observations from 06:00 (p.m., i.e. 18:00) in the evening until 15:00 (p.m.,

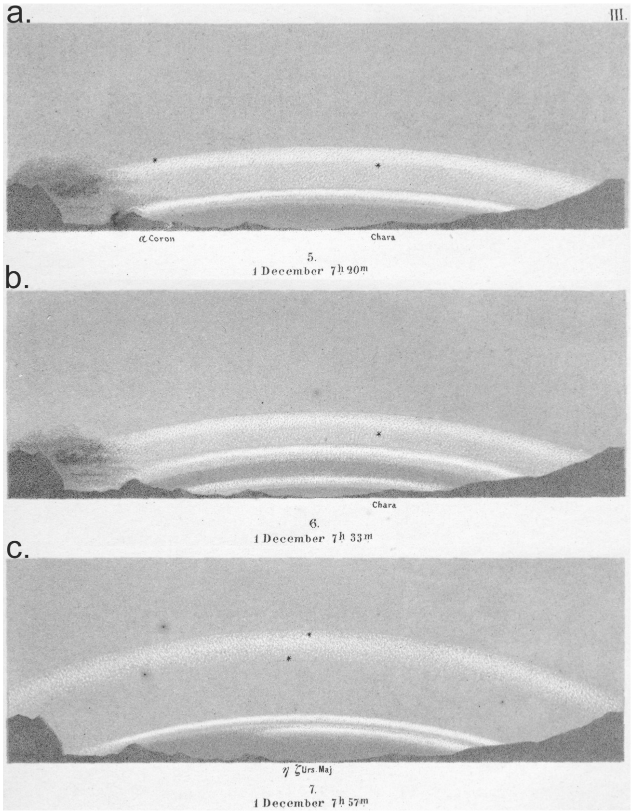

Figure 3. Tromholt's sketches of the auroral displays on 1 December 1878 (from Tromholt, 1880a).

i.e. 03:00) in the early morning. In addition, Tromholt made several sketches of the auroras for illustration of his observations. A sequence of these is displayed in Fig. 3. Most of the other stations submitted short notes like, for instance, Hemnes: "*Much aurora*" or Jockmock: "*Aurora*". A few of the other stations submitted more extended reports. The reports from 41 further stations takes altogether 138 lines – less than half of Tromholt's report, but still the best result so far.

Many scientists would have given-up to extract useful information from this inhomogeneous material. But Sophus Tromholt made a thorough analysis of all the reports. First he considered the characteristics of the individual auroras like their shape, colour, ray structure, number of arcs and movement and made a number of valid statements. In particular he noted the occurrence of the "dark segment", usually the darker region beneath auroral arcs, but occasionally also seen in-between arcs. He was inclined to consider the dark segments to be formed by clouds but opened the possibility that they might form some transition between auroras and clouds and reported observations (p. 115, in translation) that "*they in a striking manner have indicated the connection between or the influence from auroras on cloudiness*."

Tromholt was aware that presence of auroras in his observations from Bergen and absence of auroras in nearby places could be caused by missing observations or lack of reporting;

Table 1. Relative occurrence frequency of auroras vs. latitude in Scandinavia. From Tromholt (1880a).

Scandinavian Region	I	II	III	IV	V
Latitude range	71–68°	68–65°	65–62°	62–59°	59–55°
Relative aurora occ.	100	30.6	18.2	12.6	7.6

hence he took another approach. When with great certainty he could exclude occurrence of auroras in Bergen and auroras were reported from elsewhere then he assumed the reason to be the localized nature of auroras in combination with their low heights. Thus, lack of sights from Bergen of auroras observed elsewhere could be caused by the shielding effects of the intervening mountain ridges. Based on that assumption and a careful mapping of the landscape around Bergen he examined all observations and attempted to deduce the heights of the auroras from 32 specific cases. The results for the upper height of the auroras range from 70 km and down to 2 km. However, Tromholt was not quite certain and expresses in vague terms (p. 133, in translation) that "*although these results may lack the required certainty, they indicate that the regions of auroras are often to be found rather close to the surface of the Earth*". Then, quite unusual for Sophus Tromholt, he hurried to quote witnesses of cases of low auroral heights, or even auroras rising from the ground, made by prominent and trustworthy persons.

With the comprehensive material now available Tromholt attempted to provide accurate figures of the distribution of auroral occurrences over Scandinavia. He divided the entire region into 5 segments of each 3 degrees in latitudinal width. Then he corrected for the differences in number of stations and size of exposed areas to obtain a latitudinal profile. The results are displayed in Table 1 (from p. 135). It is evident from the table that the occurrence frequency rises against north in a way that seems very likely considering the actual epoch with minimum sunspots.

Tromholt, furthermore, realized that the moon phase has a definite influence on the occurrence of reported auroras. During the days around full moon there were relatively few observations of auroras. He exempted observations made 7 days before and 3 days after full moon and found now that auroras were observed all nights, except one. He then concluded that (p. 138, in translation) "*the documentation of the fact that even in a minimum year there is hardly a single night without an aurora appearing somewhere within the rather limited region spanned by the three Nordic countries, is the second important result of the observations made during the winter 1878–79.*"

An attempt to see the influence on auroral occurrence frequencies from the sunspot occurrences varying with the 27-days solar rotation period gave no definite results and Tromholt realized that the solar rotation period is too close to the moon's period to separate the two effects on the present limited data basis. He also examined the possible relation between magnetic deflections represented by two daily measurements made in Christiania by professor Fearnley (p. 139). Not surprisingly, he only detected a clear correspondence between magnetic variations and auroras for the strong event in the evening of 1 December 1878.

With his extraordinaire thoroughness, Tromholt also examined the possible relations between auroras and the meteorological parameters, barometer stand, temperatures, winds and clouds. For each day he calculated mean values for each region to be compared with the observed auroras. However, with the occurrences of auroras almost every night he concluded that such investigations could not possibly give any definite result (p. 139).

At the end of his comprehensive report to the Academy (Tromholt, 1880a), against the advice from professor Mohn, he includes a chapter on audible sounds from the auroras, a topic, which was a major issue for the contemporary scientific discussions of auroras. Since ancient times there have been reports on auroral sounds characterized as "clattering", "whispering", "whistling", "crackling" or "squeaking" observed to vary in line with strong and colourful auroras. Prominent scientist have given diverging statements concerning auroral sounds and Tromholt is somewhat ambiguous since he never himself heard such sounds associated with auroras. He states (p. 140, in translation) that "*I for my part am fully convinced that one could not possibly deny the existence of this mysterious sound*". He refers faithfully the various reports on auroral sounds, among others, from professor Hansteen from Christiania (Hansteen, 1859) and other esteemed persons. Moreover, he refers the statements given by his father, Johan Peter Tromholdt (Tromholdt, 1860) and to his grandfather (born in 1778), who spent his youth close to Viborg in Jutland and often observed strong, colourful auroras in the open field and, occasionally, in quiet weather has heard whistling related to the aurora.

In summary, Tromholt's report provides quite many precise characteristics on auroral structures, orientations, colours and movements. Further, he derives a consistent latitudinal profile for their occurrence frequency noting, correctly, that auroras occur almost every night at the northernmost latitudes (in Scandinavia) but concludes, erroneously, that auroras mostly are quite localized and occur at low heights. Finally, he examines meticulously their association with magnetic variations and meteorological conditions. Quite a comprehensive study!

5 Periods of the auroras

At the time of Tromholts huge efforts to establish coordinated auroral observations, the director of the Danish Meteorological Institute, Niels H. C. Hoffmeyer, was heavily involved in the preparations for the First International Polar Year to take place during 1882/83 close to the anticipated sunspot maximum in 1883–1884. The initiative to conduct internationally coordinated observations in the Polar Regions in the fields of meteorology and geophysics came from the Austrian scientist and arctic explorer, Carl Weyprecht (1838–1881). Various tasks were defined for the 13 countries participating in the Polar Year venture. For Denmark the appointed activity was for the Danish Meteorological Institute to send an expedition to Godthaab (now: Nuuk) at the West coast of Greenland to conduct meteorological, geomagnetic and auroral observations during one year. To lead the expedition, Hoffmeyer employed Adam F. W. Paulsen, who as a university-educated teacher at the Metropolitan School in Copenhagen had written the popular text book on physics: *Naturkræfterne* (Forces of the Nature), vol. I–III (Paulsen, 1874–1879).

Director Hoffmeyer had obtained a close contact to Sophus Tromholt through the efforts to collect auroral observations from the entire Scandinavian region including the Danish weather stations, and he might also be familiar with the submission by professor Mohn, director of the Norwegian Meteorological Institute, of Tromholt's publication to Christiania Science Academy. Now, as a further preparation for the Polar Year, Hoffmeyer asked Tromholt to analyze auroral data collected at the Danish weather stations located at Stykkisholm in Iceland and Jacobshavn (now: Ilullissat), Ivigtut, Upernavik, Sukkertoppen (now: Maniitsoq), and Godthaab (now: Nuuk) in Greenland.

Among these, the data series from Godthaab was by far the longest and the most comprehensive and reliable series of auroral observations. It was based on notes made by Samuel Petrus Kleinschmidt (1814–1886), who in addition to being a teacher at the *Seminarium* (College of Education) in Godthaab (Wilhjelm, 2001) was a careful meteorological observer and sincerely interested in auroras. Almost every day during the years from 1865 to 1882 he took a walk around the town at fixed hours three times a day; in the morning at 04:00–05:00, at noon at 12:00–13:00, and in the evening at around 21:00 LT to observe and report on the weather. During the morning and evening hours he also kept look-out for auroras. The occurrences of auroras were carefully noted in the weather reports with added indication of their characteristics in 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. In addition to these auroral observations the weather reports also provided data on the cloud cover – an important parameter for analyses of auroral data.

Sophus Tromholt, used to deal with the sparse, incomplete and often inaccurate auroral observations reported to him from a variety of observers during the Scandinavian campaign in 1878/79, immediately recognized that Kleinschmidt's stringent auroral observations was a unique resource for analyses of the auroras at this location poleward of the maximum of auroral occurrences. His analyses of the auroral observations from Iceland and Greenland and his results are reported in: "*Périodes de l'Aurore Boréale* " (On the periods of the auroras) (Tromholt, 1882a). A review is provided by Stauning (2011); hence only a summary shall be given here.

In his analyses of Kleinschmidt's auroral observations from Godthaab, Tromholt considered the reportings of cloudiness that were part of the daily weather reports. He noticed that the cloudiness and the occurrence of auroras were inversely proportional and deduced, correctly, that clouds would prevent observations of auroras. Other reports (e.g. Weyprecht, 1878) had claimed that auroras would enhance the cloudiness such that the two parameters would rise or decay together. Tromholt used the inverse relation to correct the observed number of auroras to make the data more representatives of the real aurora occurrence frequencies.

With these data Tromholt analyzed the solar cycle, the seasonal and the daily variations in the geographical distribution (relative to Godthaab) and the occurrence frequency of auroras. For the solar cycle variations he obtained the sunspot numbers (Wolf, 1860) through direct correspondence with R. Wolf. One of his most important results (Tromholt, 1882a, p. 12, in translation) is that for this very high latitude there "*not only is no direct parallisme, but on the contrary an almost complete contrast between aurora and sunspot occurrences*". Thus, during high solar activity the relative occurrence frequency at Godthaab was low and vice versa. Tromholt interpreted this variation as a consequence of movements in the belt of maximum auroral occurrence with solar activity, such that the belt was displaced southward (equatorward) during sunspot maximum.

For the seasonal variations Tromholt found maximum auroral occurrences at midwinter contrary to observations at temperate latitudes where the maximum frequency is usually found at equinoxes. He agreed with the explanation given by Weyprecht (1878) that the region of maximum auroral occurrence rises toward the North at winter solstices and retreats to the South at equinoxes. At that time Tromholt had the idea that there should be a second maximum in auroral occurrence frequency at summer solstice, but since the Sun is shining during the arctic summer nights, he had no observations to prove that theory.

To describe the daily variations, Tromholt had only the occurrences of auroras made by Kleinschmidt in the evening at around 21:00 (i.e. close to midnight in local magnetic time) and in the morning at around 04:00–05:00 LT. He was aware that Godthaab is located in the northern outskirt of the auroral belt such that auroras are mostly observed to the South. Thus he divided the observed auroras in two groups, one far to the South and another closer to zenith. For the evening auroras the occurrence frequencies were about the same for the two groups while in the morning observations the occurrences of auroras were more frequent close to zenith than far south. From these statistical results he concluded (Tromholt, 1882a, p. 36, in translation) that "*This important and with great certainty derived result gives evidence that the auroral zone in its daily walk travels northward during the night.*"

This is the first published indication of the local time variations in the belt of auroras that 80 yr later was characterized by Khorosheva (1962) and Feldstein (1963) in terms 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.

In addition to the three auroral periods related to the solar cycle, the seasonal, and the daily variations, respectively, Tromholt was aware of the possible variations in auroral occurrence frequency with the Sun's mean 27 days rotational period and with the Moon's 28 days period. However, he found again that these two periods are so close in duration that they mask each other and inhibit efforts to separate their effects.

With the auroral data, no corresponding magnetic observations were available from the stations in Iceland and Greenland. For the possible relations between auroras and magnetic variations, Tromholt (1882a) only made general remarks based on various sources. The available notes on auroral observations have no height information; hence Tromholt, contrary to his report from 1880, abstained from discussions of their height. He mentions the notes made by Kleinschmidt describing the auroras as usually colourless like the moonlight except for rare cases of red auroras and the occasional red and green colours observed at auroras in strong motion. Concerning possible auroral sounds, Tromholt refers faithfully (p. 31, in translation) Kleinschmidt's statement that "*I never ever have observed any sound related to the aurora, despite my hearing generally has been quite good*".

From his work it is clear that Tromholt took a modern scientific approach to the auroral phenomenon. Rather than jumping to premature theories he explains (Tromholt 1882a, p. 57 in translation): "*The time for bringing forward an adequate aurora theory has not yet arrived. For yet some time observations are needed. Not sporadic and random but organized according to strict principles as the other meteorological observations. For this reason I have taken on me the task to provide an observational region larger and a material more comprehensive than ever seen before*."

Tromholts publication (Tromholt, 1882a) on the auroral observations from Iceland and Greenland is excellent analytical work and was highly praised by director Hoffmeyer, who wrote in the introduction to the article (in translation): "*The aurora is still in many respects an unexplained phenomenon, and every contribution to its enlightenment must be received with gratitude. It must be with exceedingly great satisfaction that Mr. Tromholt has been able to provide such a valuable contribution to an issue that has occupied the thoughts of famous scientists*."

6 Book of star maps

Professor Henrik Mohn, director of the Norwegian Meteorological Institute, encouraged Tromholt to make star maps to be used for the auroral observations made by the Meteorological Institute in Christiania. Being very proficient in astronomy, Sophus Tromholt undertook this task. The result (Tromholt, 1879a) was a very nice book in a large-sized format: *Stjernekarter til brug ved Nordlysiagttagelser. Konstruerede og udgivne paa Foranledning af det Meteorologiske Institut i Christiania*. (Star maps for use at auroral observations. Constructed and published at the request of the Meteorological Institute in Christiania). It holds six pages of introduction text and five very detailed and nicely printed star maps drawn from Tromholt's constructions. Tromholt explains how such star maps are constructed, how to calculate rectascension and declination, and he provides extensive instructions for the use of star maps for auroral observations. These star maps came in extensive use by observations conducted by further auroral scientists, among others, from Edingburg and Montreal.

For Tromholt the publishing of the star maps must have been felt as a breakthrough for him and for his research. In the introduction he wrote (p. 3, in translation): "*The transient play of rays and the vivid shimmering of colours have, so far, escaped the ties by the laws of science. We are reduced to guessing not just with regard to the essential: the real cause and nature of the aurora, but virtually with everything associated with this phenomenon*." With this statement Tromholt rejected past theories on auroras and stressed the need for further observational evidence on the aurora. Among the main purposes of the star maps was their use for the estimations of the height of the aurora, which in his opinion was essential to understand the nature of the aurora.

7 The first Polar Year – observations from Bossekop and Kautokeino

With the successful publication of his star maps (Tromholt, 1879a), with the report to the Academy of Science (Tromholt, 1880a) and other publications (Tromholt, 1881c) on the auroral observations from Scandinavia during the winter 1878/79, and with the report on the auroral periods (Tromholt, 1882a, b), Tromholt took a profound interest in the approaching International Polar Year. His triangulation of observations from many places in Scandinavia of the auroras on 17 March 1880 (Tromholt, 1880b, c, 1882i) had given an average height of 147 km for the lower border of auroras. To verify and extend such observations he suggested to professor Mohn to establish a corresponding station in Kautokeino, around 100 km south of the Norwegian Polar Year observatory Bossekop, and install a telegraph line between the two stations. Mohn replied that a telegraph line would be too expensive but agreed to supply some instruments to Tromholt's expedition.

For the fiscal year 1881/82 Tromholt succeeded to obtain direct support from the Norwegian Parliament for his research through a 5-yr period; he was granted 1000 kr. a year, only, a quarter of his salary as a teacher. Furthermore, he was granted 2000 kr. from Captain I. C. Jacobsen, founder of *Carlsberg Brewery* in Copenhagen for the expedition, probably on recommendation from Hoffmeyer. Altogether Tromholt received 6700 kr from I. C. Jacobsen without which his auroral expeditions would not have been possible. In addition, a wealthy merchant, C. Sundt, from Bergen provided him 400 kr to purchase a camera and photographic plates to bring to Kautokeino on the condition that the acquired photos were donated to the Museum in Bergen. Now, a collection of the original photos is held at the University Library in Bergen.

From these modest resources Tromholt prepared his one-man expedition to Kautokeino and the set-up of instruments for an alternative Polar Year Observatory. He applied for a leave from his position at the Tank's School in order to concentrate on auroral research; he never came back to teaching. On 24 August 1882 he left Bergen onboard the postal steamship heading for Bossekop via Tromsø in Northern Norway. Up to and during the expedition he wrote scientific notes (Tromholt, 1882h, i, j, 1883a, b, c, d), and popular science articles (Tromholt, 1882c, d, e, f, g) on auroras and observations. Furthermore, he wrote travelogues in letters to the Norwegian newspaper *Morgenbladet*. These letters were later in an expanded form published in his book: *Under the Rays of the Aurora Borealis* (Tromholt, 1885a; in Danish: 1885b).

Arrived in Bossekop he visited the Norwegian Polar Year Observatory headed by Axel S. Steen. Tromholt's intention with the visit was, among other, to study the techniques used there for geomagnetic and auroral observations and to settle agreements on joint simultaneous auroral observations from Bossekop and Kautokeino. At Bossekop five men took shifts of observations round the clock. Generally, all meteorological and geomagnetic instruments were read-off once every hour. Between 05:00 and 11:00 p.m., auroral observations were added at 15 min past the hour. Possible auroral forms should be drawn on paper stretched over a light well, and it was agreed that sightings to auroras should be made in the common vertical plane for Bossekop and Kautokeino (close to the magnetic meridian plane). The hour between 08:00 and 09:00 p.m. was a particular "aurora hour" during which the observations should be made every 10 min.

From Bossekop Tromholt continued the journey to Kautokeino with his heavy equipment. There was no road between the two locations. At start the travel was by horses and Tromholt's equipment had to be relocated in smaller cases to be loaded on horse backs. Later, the journey continued up-stream on Sami "river-boats". It took Tromholt and his travel companions, among others the local vassal, a week's exhausting travel by boat and on foot to reach Kautokeino. Here he was installed in the vassal's residence and began to set up his observatory.

Tromholt's auroral observatory in Kautokeino is illustrated in Fig. 4. Tromholt is dressed in his warm Sami-costume.

Figure 4. Tromholt in Sami costume standing among the instruments in his ”observatory” in Kautokeino (Tromholt, from photo collection held at University of Bergen Library, UBB).

In the middle the most important instrument, a combined aurora-theodolite and astronomical star-transit instrument, is mounted on a brickwork construction – not an easy mount at a place void of bricks, cement and bricklayers. Around the instrument was built a small wooden hut of which the upper part could be folded down when the instrument was in use. To the right is placed a cabinet holding various items to be of use during the observations such as star maps, catalogues, and lanterns. Around the central instruments various stands were placed for mounting of the light well, for rain and snow gauges and for the camera for photographing the auroras. Rather simple, but as it turned out, quite effective.

In his quarter at the vassal's residence Tromholt arranged a dark-room and a study in which he kept the precious chronometer, so important for correct timing of the observations. At the gable he attached a tall rod with an iron point mounted at the end from which an electrical wire passed to his study for measurements of “air-electricity”. Finally, for measurements of “earth-currents”, long buried wires were connected to large copper plates dugged north and south, respectively, of the house.

Tromholt conducted a quite demanding observations routine. He made observations every day from 21 September 1882 to 15 April 1883 with the exception of the interval from 22 to 27 February where he took a journey by sledge to Muonioska in Finland and Karesuando in Sweden. From getting dark and till midnight he serviced the instruments unless the sky was overcast. At 10 min past the hour he made observations to be correlated with those from Sodankylä. 5 min later he made observations to be correlated with those from Bossekop. During the “aurora hour” from 08:00 to 09:00 p.m. the observations should be made every 5 min. In case of active auroras the observations were extended through the night. To assist him during the morning observations (probably just by observing if there were auroras) he hired a Same, Henrik Pentha. At the observatories in Bossekop and Sodankylä, for comparison, several trained staff members shared the corresponding tasks.

In addition, he had to fight the weather conditions. In his book *Under the rays of the aurora borealis* (Tromholt, 1885a) he describes the observational conditions during the frequent occurrence of cold weather down to minus 50 °C: “*When, for instance, every hair in one's moustache is transformed into spikes of ice projecting like the quills of a porcupine; when the faintest breath blurs the spectacles at the very moment when I am most anxiously watching the dial of the chronometer for an imminent transit observation; when every instrument is, as soon as exposed, covered with a layer of hoar frost, which obliterates the figures, and the lens of the telescope has every minute to be cleared of a sheet of ice; when the fingers adhere to the metallic parts with a singeing pain as when touching red-hot iron, and when finally, the lamps go out, through the oil freezing, as you are in the middle of an important note – well, under such trying circumstances a man might be excused slipping a big d.....*” (vol. 1, p. 95).

The book (Tromholt, 1885a) holds an extended chapter on auroras. The chapter is a mix of a text book on auroras and descriptions of his observations from Kautokeino. The text book part is very good, considering the contemporary state of knowledge concerning the aurora. It holds a historical account of auroral observations and of the development of theories for this mysterious phenomenon. Furthermore, the chapter holds sections on the visual appearance of auroras. Among these there are several impressive descriptions of auroral break-ups – "*auroral substorms*" in modern terms.

Tromholt also discusses the classification of auroras introduced by Weyprecht (1878). He argues that auroral arcs, bands and crowns are often the same auroral form just viewed at different distances. Arcs are extended auroral forms seen from a long distance and delimited by the horizon. At closer distances, the auroral forms are seen as bands or "draperies" higher in the sky, and when they appear overhead they might be seen as crowns. He distinguishes between the extended band and the ray structures and argues (again correctly) that distinct rays are most often seen during the violent phases of vivid and colourful auroras. Finally, he considers auroral haze or brightenings without specific shape and discusses whether such forms may constitute a transitional phase between auroras and clouds.

Further, he discusses the geographical mapping of "isochasms" (curves for equal auroral occurrence frequencies), which delineates the auroral zone of maximum auroral occurrence frequency, and he provides a detailed account of the works by Loomis (1873) and Fritz (1881). He extends the concept of a continuous "auroral ring" centred at the magnetic pole, which was forwarded by Hansteen (1827). While Hansteen, Loomis and Fritz's analyses were built on statistics for auroral observations made at night depicting the auroral zone, Tromholt took the idea one step further by suggesting the existence of an instantaneous auroral belt subjected to variations with local time in addition to the seasonal and solar cycle variations. This belt is now termed the "auroral oval" (Khorosheva, 1962; Feldstein, 1963). With the Earth's rotation, the varying positions of the oval's midnight section form the auroral zone. Tromholt refers to his own work (Tromholt, 1882a) on the periods of the aurora as observed from a position poleward of the auroral zone.

Tromholt provides a detailed account of the colours of auroras and their variations with height from the violet-reddish lower border seen during strong and vivid auroras, the white-yellow-greenish colours seen most often in the auroral curtains, to the faint reddish auroral colours seen high in the sky. He also discusses auroral sounds. At this time he is quite sceptical around the existence of audible sounds related to the auroras and states quite definitely that during his extensive watching for auroras he has never heard any sound that could be related to the observed auroras even in their strongest display. Tromholt avoids to completely abandoning the possibility and notes faithfully that more than half the population in Lappland either themselves have heard sound from the auroras or know somebody who has. He lists the various descriptions of the sounds but concludes that most of these could be explained by the whistling in the wind, rustling of the leaves, the snow drift, or simply the buzzing in the ears as you tilt the head backward to watch the aurora. However, he notes (p. 284) that "*all other scientists, who have sojourned for a length of time in northern regions, have never heard the slightest sound, which could with any amount of certainty be ascribed to the Aurora Borealis*." From his own observations he reports (p. 285), "*that of all the intense aurorae I have observed in the various parts of the Arctic regions, and which I am sure I have watched with more attention than is generally bestowed on them, every one has been perfectly silent*."

He devotes an extended section to a discussion of the height of the aurora and refers the many contradicting estimates ranging from auroras observed near the ground (or even extending from ground) up to several hundreds of km, even one or two thousand km. Tromholt is quite sceptical about the low heights – mostly below 20 km – measured by Paulsen during the Polar Year expedition to Godthaab (Paulsen, 1884, 1886, 1893a). He also casts doubt to Paulsen's and other observer's reports on auroras seen below clouds or mountain peaks and states that although he has seen an abundance both of clouds and auroras, he has never observed auroras in front of or below even the highest clouds.

The most important result of his observations from Kautokeino coordinated with those from Bossekop is no doubt the estimates of the heights of the lower border of auroral arcs. With meticulous care Tromholt examines the reports and drawings of auroral forms made by the staff at the observatory in Bossekop and compares them with his own observations in order to select cases where there is no doubt that the same auroral form was observed from both sites. With the sighting angles from the two locations and their known distance of around 100 km he can calculate the heights of their lower border. He writes (p. 259): "*I have on the principle indicated in Fig. 12, made a series of preliminary measurements of the lower edge of aurorae observed at both stations, having selected only those where there cannot be the least doubt as to identity, from which I have obtained the following values in km.: 76.0, 79.9, 84.6, 93.6, 97.7, 98.2, 99.0, 100.0, 100.6, 107.0, 116.6, 124.4, 124.9, 131.9, 141.6, 144.9, 149,0, 163.8. If the average of these eighteen measurements is taken, the average height of the lower edge will be 113 km.*"

The question of the true height of auroras remained unresolved until the excellent photographic technique developed by Carl Størmer and O. A. Krogness came in use. During expeditions to Bossekop in 1910 and 1913 they arranged to have the auroras photographed simultaneously from two stations. From subsequent analyses of the sighting angles, assisted by the position of known stars in the photos, the heights of lower border of auroras could be estimated accurately (Størmer, 1911, 1955). Tromholt's results from his observations during the winter 1882/83 are remarkably close to Størmer's height estimates made almost 30 yr later with a superior technique, not only in the average value but even in the distribution of recorded heights above and below the mean value.

Figure 5. Tromholt's photo of his drawing of an auroral display ("auroral break-up") observed at 07:55 p.m. on 6 October 1882 (Tromholt, photo from UBB collection).

During his stay in Kautokeino, Tromholt attempted to photograph the aurora but his equipment was not sensitive enough for the difficult task even with exposures lasting for several minutes. Instead, he trained himself in making drawings of the auroras using as models the excellent drawings in "Voyages" made by the French expedition, "La Recherche", to Bossekop in 1838–1839. From such drawings he could then make photos, which provided beautiful illustrations of his observations like the example from 6 October 1882 shown in Fig. 5.

Actually, he succeeded on 15 March 1885 with an exposure time of 8.5 min to make a photo of an aurora seen over Christiania – possibly the first photo ever made of an aurora (Brekke and Egeland, 1994). The photo was displayed for the Norwegian "Kosmos" society and was described independently in several journals. Unfortunately, it no longer exists. The first now available auroral photo was taken by the German Martin Brendel in 1892. However, Tromholt used his precious photographic equipment and the ample amount of photographic plates carried along on the expedition to Kautokeino to make photos of people and locations. He issued in 1883 a portfolio with unique pictures from Lappland (Tromholt, 1883e). One example, a newly married Sami couple, is displayed in Fig. 6.

For the advancement of auroral science it was unfortunate that Tromholt's comprehensive and mostly quite correct descriptions of the auroras came in the form of traveller's letters to a newspaper and later were issued in a popularizing travel book (Tromholt, 1885a) rather than being issued as a science text book. However, he managed to establish close and trustful relations to the Samis, and his book holds, in addition the sections on the auroras, a collection of unique descriptions of the life and local customs among the Sami people and a series of photographs – a valuable treasure for ethnographic studies of an indigenous population. The originals of the photos are held at the University Library in Bergen (www.ub.uib.no).

Figure 6. Sami bride and groom (Tromholt, photo from UBB collection).

8 Man-made auroras in Sodankylä and Iceland

As the days grew longer during spring time, Tromholt stopped his auroral observations and made an excursion to the Finnish observatory in Sodankylä. The observatory was the result of the efforts by professor Lemström from Helsinki to establish a Finnish Polar Year observatory. The main activities at the observatory were geomagnetic measurements by magnetometers and recordings of earth currents by north-south and east-west oriented systems of electrodes buried in the ground and connected by wires in which sensitive galvanometers could be inserted to measure the currents. The station, in addition, conducted meteorological and astronomical observations (Tromholt, 1885a).

Tromholt was eager to accomplish exchange of observations after having previously agreed with professor Lemström on coordinated auroral observations from Sodankylä and Kautokeino where he, carefully, had conducted his part through the winter. Tromholt never got hold of the corresponding auroral observations from Sodankylä. They might not have been worthwhile, anyway, since even the local sightings of auroras from two positions in Sodankylä separated by 4 km and connected by telephones to obtain timing correspondence gave strongly conflicting results. Tromholt examined their sighting equipment and found no failures; hence he concluded that the inconsistent results were due to lack of skills at the observers rather than inadequate equipment.

A unique experiment had been conducted by professor Lemström. On the top of the mountain Oratunturi, a few km from Sodankylä, a so-called "aurora discharge-apparatus" was installed. It was constructed from a long copper wire mounted on telegraph poles placed in a spiral configuration to fill-out an area of 1000 square meters. Upward directed iron spikes were soldered to the copper wire each half meter. An isolated electric wire was connected to the innermost end of the copper wire and taken to the foot of the mountain around 600 feet below the discharge equipment and there connected to a metal plate buried in the ground. Electric currents could now be detected with a galvanometer inserted in the circuit.

However, the most interesting part of the experiment was the reported appearance of a weak yellow-white glow around the discharge equipment during the night, which upon spectroscopic analyses gave the same spectrum, albeit weak, as that of the aurora. Later, professor Lemström repeated his experiment with a similar apparatus installed at a mountain close to Lake Enare in the northernmost part of Finland. On one occasion an upward pointed cone of light appeared above the equipment as shown in Fig. 7. Lemström was convinced that auroras were carriers of electric currents and that he had generated an auroral discharge streatching up in the air from his equipment at the mountain top (Lemström, 1886).

In consequence, Lemström argued that auroras would occur at rather small heights or even reach ground. Tromholt was quite sceptical and wrote (Tromholt, 1885a): "*I consider, however, that it is impossible to accept these theories, and believe that the luminous phenomena are more related to the electric phenomenon known as St. Elmo's Fire than to the Aurora Borealis*" (vol. 1, p. 170). However, as a careful scientist, Tromholt made the remark that professor Lemström's interesting, but due to the conditions provisional and short-lasting, experiment should be repeated at places with better conditions than those provided by the wooded, mountain-less Lappland terrain.

The next winter, in 1883/84, Sophus Tromholt undertook a journey to Iceland. This expedition, like the journey to Kautokeino, was initially described in a series of traveller's letters to the Norwegian newspaper *Nationaltidende* and later combined to form a travel book (Tromholt, 1885c): *Breve fra Ultima Thule* (Letters from extreme Thule). Further descriptions of the expedition is given in Tromholt (1884a, b, c, d, 1885f). As part of this expedition Tromholt had prepared for a repetition of Lemström's discharge experiment. Assisted by 21 men and by hard work through several days, he managed in March 1883 to mount a similar discharge apparatus at the top of Mount Esja, 2500 feet high and close to Reykjavik in Iceland. In his installation of the spiral-shaped configuration of a copper wire with added spikes every half meter, mounted at poles on top of Esja and connected by insulated electrical wires to a metal plate buried in the ground at the foot of the mountain, there was no galvanometer inserted. Hence, he did not observe possible electric currents.

Figure 7. Image of the reported operation of Lemström's "aurora discharge generator" (from Lemström, 1886).

From his residence in Reykjavik at a distance of 14 km from Esja, Tromholt watched the mountain by binoculars every night hoping to observe the possible "auroral glow" around the top where his discharge apparatus was mounted. However, the observations failed to indicate any special glow around the mountain – much less an auroral ray emerging from the discharge equipment at its top. Tromholt submitted an article to the science journal "*Nature*" (Tromholt, 1984c) to describe his experiment and emphasize the negative results. In Tromholt (1885c, p. 98, in translation), he concluded that "*even a negative result is on this occasion a result of interest for the science*".

Lemström was quite offended by Tromholt's criticism of his discharge experiment. He explains in a note appended to his book "*Polarljuset*" (Lemström, 1886, p. 168–169) the reasons why Tromholt failed to observe the glow at the experiment in Iceland. The primary reason being that Tromholt was watching the mountain from an excessive distance of 14 km, where the light intensity has decreased to 1/12 of the initial value of the glow seen best from a distance of 1.54 km. Furthermore, the season (springtime) was not favourable and the year (1884) was lacking strong auroras. Even worse, Tromholt was not using a spectroscope (Lemströms favourite instrument) to identify the observed light.

In addition to the chapter on the discharge experiment, Tromholt's book (1885c) holds a series of sightseeing travelogues from visits to tourist attractions around in Iceland and to various further places, among others, the Faroe Islands. He wrote the traveller's letters in a humorous, ironic and often derogatory tone, which at times aroused strong reactions from the offended readers.

9 Dispute between Sophus Tromholt and Adam Paulsen

In his early report to the Norwegian Science Academy (Tromholt, 1880a), Tromholt argues from the strong differences in auroral observations between close locations separated by mountain ridges that auroras may occur rather close to the ground. However, already from the observations made on 17 March 1880, he derived an altitude of 147 km based on triangulation of a strong aurora seen from different places (Tromholt, 1880c, 1881b). His observations from Kautokeino further substantiated his view that auroras occur at altitudes of around 100 km or more, high above the clouds. In his book (Tromholt, 1885a, vol. 1, p. 260) he states: "*although always paying the closest attention to this particular point, I have never even seen a fragment of an aurora in front of or below the clouds. Even the most intense development of light, colour, and motion occurred always above what seemed to be the very highest lying clouds*."

On the contrary, Adam Paulsen (Fig. 8) from his observations made in Godthaab during the Polar Year Expedition in 1882/83 believed that auroras were the result of electrical discharges reaching the ground – at least within the "home of the auroras" at high latitudes. Thus, auroras in his opinion could be seen at very low altitudes. In several of his publications from the expedition (Paulsen, 1884, 1886, 1893a), he reports on auroras seen below the clouds or mountain tops. From two locations separated by 5.8 km the expedition made simultaneous estimates of the viewing angles to the lower border of auroras. Of 31 such cases 9 were rejected because they gave differences in the parallax of less than 1°, which were considered to give unrealistic large altitudes and to fall within the uncertainty of the observational method. Eight of the remaining cases gave heights between 19 and 68 km while the rest gave heights between 0.6 and 9.8 km (Paulsen, 1884, 1886). Paulsen was supported in his view by similar observations made in 1885 by Garde and Eberlein from Nanortalik in Greenland, where they used a baseline of 1249 m between the two observing sites and derived auroral heights between 1.8 and 15.5 km (Paulsen, 1886, 1893a). Thus there was a substantial conflict between Tromholt's and Paulsen's views on the height of the auroras.

The conflict of views was perhaps even stronger concerning the interpretation of the variations in the latitudes of the observed auroras. In his report in the Yearbook for 1880 from the Danish Meteorological Institute (Tromholt, 1882a) and in many further publications, Tromholt argued that the daily, the seasonal and the solar-cycle related variations in the occurrences of auroras were caused by displacements of the belt of auroras. He was not specific regarding the cause of the displacements but stated quite often that the explanations were subjects for future auroral research. Paulsen, on the contrary, had a theory for the aurora according to which the auroral currents and associated displays were related to negative ions created by the solar illumination particularly near equator in the middle of the day and then streaming poleward and on to the nightside of the Earth. Here they would form an immense negative cloud that would emit "cathode rays" (much like the cathode in discharge tubes), which in turn would excite the atmospheric constituents and cause auroras. In consequence, any enhancement of the auroras at lower latitudes, whereby the stream of negative ions was diverted earlier, would automatically weaken the auroras at higher latitudes.

Figure 8. Adam F. W. Paulsen (Litograph, A., Ecksteins Verlag, Berlin).

In his bulletin from 1889 (Paulsen, 1889) to the Royal Danish Academy, Paulsen strongly criticises the statistical treatment of Kleinschmidt's observations from which Tromholt deduced the daily oscillations in the latitude of maximum auroral occurrences and cast doubt on Tromholt's results concerning the seasonal and solar cycle related variations in the latitude of the auroras. The fairly strong criticism of Tromholt's results on the variations in auroral occurrences and his estimates of auroral heights were repeated in several publications (Paulsen, 1889, 1893b, 1894). At times Paulsen is quite devaluing on Tromholt's analyses. In an article in *Pettermanns Mittheilungen* in 1892 (Tromholt, 1892), Tromholt argued against Paulsens criticism and reported the results on auroral heights obtained during his Polar Year expedition to Kautokeino.

However, it seems that Paulsen had the upper hand in these disputes, possibly because of his university education, his renowned text books in physics, and his status as the director of the Danish Meteorological Institute. Paulsen's view on low auroral heights survived in the "*Encyclopedia*

Britannica" even up to 1911 where a paragraph in the reference on the aurora reads: "*Much the consistent results were obtained at Godthaab by Paulsen. The base was 5.8 km (about 3.2 miles) long, the ends being in the same magnetic meridian, on opposite sides of a fiord, and observations confined to this meridian, strict simultaneity being secured by signals. Heights were calculated only when the observed parallax exceeded 1° but this happened in three-fourths of the cases. The calculated heights – all referring to the lowest border of the aurora – varied from 0.6 to 67.8 km (about 0.4 to 42 m.), the average being about 20 km (12 m.)*". Tromholt's results are not mentioned. The question on daily oscillations in the region of maximum auroral occurrences remained unsettled until the documentation of the auroral oval appeared in the brilliant works by Khorosheva (1962) and Feldstein (1963).

10 Tromholt's study of telegraphic disturbances during auroral activity

The disturbance of telegraphic lines during auroral activity was known since the great Carrington storm in August–September 1859. Such disturbances have haunted the telegraphic communication particularly in regions close to the auroral zone. In their mildest form such disturbances could cause errors in the transmitted messages. In stronger cases the telegraph communication could be completely disabled and in the worst cases the telegraphic equipment was turned into a sparking inferno.

Tromholt was aware of the close relation between auroras and such telegraphic disturbances. He saw in these events an opportunity to enhance visual auroral observations and, in particular, to extend them over the light hours of the day and through the arctic summer where the Sun never sets in order to obtain better statistics for the real occurrence frequency of auroras irrespective of the visual conditions. He was also aware that thunderstorms could produce similar disturbances but noted that these, generally, are restricted to quite limited regions.

On Tromholt's request 44 telegraph stations in Norway and Sweden had since 1 July 1881, made account of all transmission disturbances on the telegraph lines with indication of time, duration, strength and other characteristics. For his book (Tromholt, 1885a), he had data available for the three years, 1881–1884. From these data he selected four representative Norwegian stations, Kistrand (at 70° N latitude), Lødingen (68°), Trondhjem (63°) and Bergen (60°). Tromholt excluded thunderstorm-related (local) disturbances. From the remaining amount of data for telegraph disturbances he deduced the daily and the seasonal variations in the activity associated with auroras. His results for the seasonal variations displayed in Fig. 9 depict the early spring and late autumn maxima and the midwinter minimum in occurrences also known from visual auroral observations

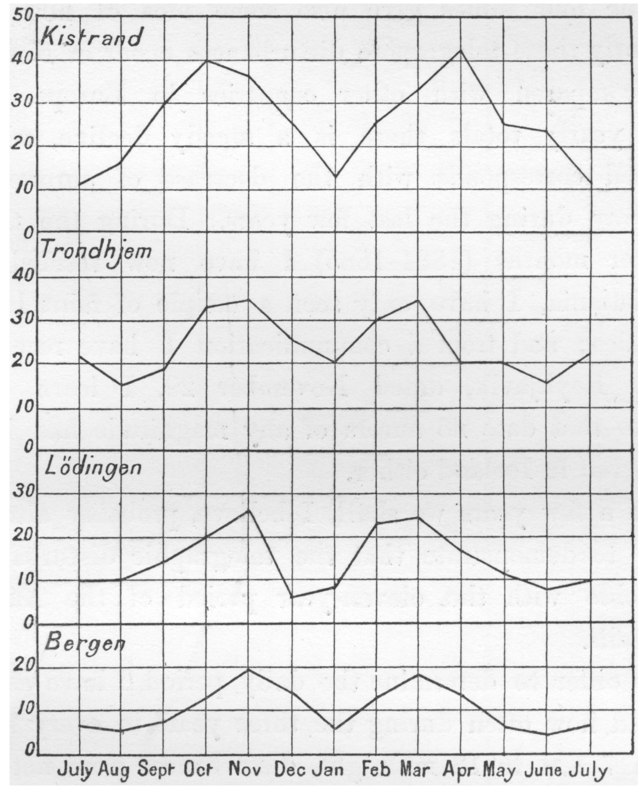

Figure 9. Seasonal variation in no. of occurrences of aurora-related disturbances on telegraph lines (from Tromholt, 1885a, vol. 1, p. 279).

at moderate latitudes. Most importantly, he derived also the mid-summer minimum in auroral activity, which could be hard to establish with certainty from visual observations impaired by the excessive duration of the daytime light interval at high latitudes.

Furthermore, Tromholt established the daily variation in such disturbances and deduced a daily maximum in the occurrences of disturbances in the evening at around 08:00–09:00 p.m. He found a secondary maximum at forenoon around 10:00–11:00 a.m. and a weak minimum at midday around 02:00 p.m. There are not much data from late in the evening until 07:00 or 08:00 in the morning, as the telegraph stations were probably closed during the night. Tromholt noticed the decay in occurrences over the examined years and interpreted that variation in terms of the concurrent decrease in solar activity. However, he noted with humble reservation, that "*these observations will only become of real scientific value when we have a series of them extending over many years before us.*" (Tromholt, 1885a, vol. 1, p. 277).

In addition to the chapter in his book (Tromholt, 1885a), Tromholt wrote several science articles on the telegraphic disturbances related to auroras (Tromholt, 1885h, i, m).

11 Tromholt's final works and his catalogue of auroral observations

Throughout his stay in Norway, Tromholt tried to establish a position that would allow him to devote his full time to auroral research. In a letter dated 30 October 1880, to professor Mohn, director of the Meteorological Institute in Christiania, he suggested that a division of the Norwegian Meteorological Institute devoted to studies of the auroras should be established in Bergen with him, Sophus Tromholt, as its director. In his 20 pages letter, Tromholt details the anticipated budget for this institute and the number of employees. From later communications it is clear that professor Mohn, in polite terms, rejected the proposal. Thus Tromholt continued for a while his employment as a teacher at the Tank's school in Bergen.

Since the fiscal year 1881/82 Tromholt, on the recommendations from, among others, professor Mohn and professor Fearnley from the University in Christiania, was awarded a yearly support of 1000 kr through 5 yr. This support in combination with private donations to his expeditions, and some income from newspaper articles and a series of quite successful public talks on astronomy and other science topics, allowed him to take leave from his employment as a school teacher since the middle of 1882 never to return to that position.

In June 1882 Tromholt issued a printed note to a range of Norwegian authorities and institutes and to many prominent persons, among others, professor Mohn in Christiania and professor Rubenson in Uppsala, with a proposal to establish in Trondhjem a Centre (*Etablissement*) for auroral research. The idea is further promoted in his article *An observatory for aurorae* in the science journal *Nature* (Tromholt, 1882j). In his justification of the centre, Tromholt argues that Norway, more than any other country, has the background for solving the riddle of the aurora and the mystery of geomagnetism. He further argues that the telegraph line between Bergen and Trondhjem, an important resource for auroral research, is the one in the world positioned closest to the North Pole.

In his note Tromholt mentioned his results from the auroral campaign in 1878/79 (Tromholt, 1880a). For the following season, 1879/80, he collected 1600 observations from all over Scandinavia for a total of 249 auroras. For the season 1880/81 he reported to have 5200 observations of 300 auroras at hand, while for the season 1881/82 he anticipated the collection of an even larger material since he corresponded with 1000–1500 observers. Tromholt submitted a formal proposal to the Norwegian government to establish the centre in Trondhjem and applied for a yearly salary of 4000 kr for himself. However, the proposal was rejected.

In addition to his own auroral observations, Tromholt was extremely interested in collecting observations and other evidence of past auroras. He had sent more than 1000 questionnaires to people all over Scandinavia asking for their reports on auroras in questions such as: "*Which years in the present century were particularly rich in auroras?*". Furthermore he asked in the questionnaire whether the auroras have shown any influence on the weather and whether sounds have been heard from auroras. Furthermore he visited archives and libraries in Bergen, Trondhjem, Christiania, Copenhagen and Leipzig to collect notes on auroras from books, journals, travelogues, unpublished manuscripts and newspapers. And he published a number of science notes and popular articles on the history of auroral observations, among other, reports on auroral sounds (Tromholt, 1885d, e, g, j, k, l, n, o).

In all Tromholt collected 5887 reports on observations of auroras from Norway for the years 1761–1878. He tried hard to obtain support to handle the collected material. In 1884 he applied the Norwegian Parliament, "Storthinget", for 4000 kr in support to allow him to analyse the auroral observations made prior to 1878 and, furthermore, 5000 kr to print a Norwegian catalogue of past auroral observations. However, he obtained no more than the continuation of the yearly grant of 1000 kr for each of the years 1885 and 1886. Afterwards, he was denied further support.

In 1886 he ran out of means and since further applications for support from the Norwegian government were not granted, Tromholt had to pack his huge material on auroral observations and leave Norway to seek income from giving public lectures abroad, first in Denmark and later in Germany, to supplement the sparse income from his books (Tromholt, 1885a, b, 1887, 1889). In 1887 he married Maria Margretha Jess (1866–1948) born in Flensburg, Schleswig (since 1864 part of Germany). The couple moved to Germany where Maria took education at the Academy of Music in Leipzig to become an opera singer.

In 1890 he again applied for funding from the Norwegian parliament to publish the catalogue of auroral observations. His application was recommended by the science faculty council at the University in Christiania and by professor Rubenson from Uppsala, Sweden and forwarded from the parliament to the government but then rejected. Tromholt, now residing in Leipzig, Germany, with all his observational material but without means to publish them in a book, wrote in the foreword of an article to *Pettermanns Mitteilungen* (Tromholt, 1892, p. 201) that came to be his last publication on auroras: "*Nachdem meine über eine ganze Reihe von Jahren sich erstreckenden Bemühungen, von seite der norwegischen Staatsautoritäten die nötige Unterstützung zur Fortführung der von mir ins Leben gerufenen, umfassenden Untersuchungen über das Nordlicht zu erhalten, immer und immer wieder gescheitert waren – nachdem mir schiesslicht auch sogar die nur für den druck der von mir zusammengestelten Werke erforderlischen Mittel Jahr für Jahr verweigert wurden, sah ich mich im Herbste 1886 gezwungen, meine Thätigkeit auf dem Gebiete der Nordlichtforschung aufzugeben und das ganze Unternehmen fallen zu lassen. Das große, seit 1878 aus allen nordischen Ländern eingesammelte Beobachtungsmaterial wurde verpackt, und ich verließ Norwegen, um in Auslande*

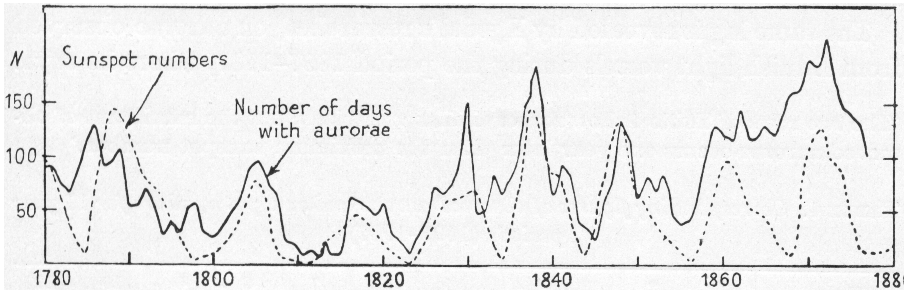

Figure 10. Comparison of sunspot number (Wolf, 1860) with number of days (nights) with observed auroras. Reproduced from data in Tromholt (1898) (Tromholt, 1898; here from Størmer, 1955).

astronomische Projectionsvorträge zu halten." (Since my efforts, through an extended span of years, to obtain from the Norwegian authorities the support needed to accomplish the mission of my life, the comprehensive investigations of the aurora, were rejected again and again – and since, finally, the means needed for the printing of my collected works were denied me, then I had to give up my work on auroral research and drop the entire enterprise. The large observational material collected from all the Nordic countries since 1878 was packed, and I left Norway to make lecture tours on astronomy abroad.)

Further in the foreword he describes his decision to publish his comprehensive auroral observational material in spite of the sparse time left for scientific research in consequence of his profession as travelling lecturer. He mentions two ongoing works; the one is an entity in three parts of which the first should be a review of his Polar Year auroral observations made during the winter 1882/83 from Kautokeino in conjunction with observations from the Norwegian station at Bossekop. The second part should deal with the large amount of auroral observations he had collected during 1882/83 from all over Northern Europe. The third part should hold a review of the telegraph disturbances reported from around 40 stations during 1882 and 1883 (note: these observations include disturbances observed during summertime). The articles in *Pettermanns Mitteilungen* (Tromholt, 1892, p. 201–214, 236–240 and 259–262) hold rather brief reviews of the three parts of his first work.

The second work should be a completed Norwegian catalogue of all existing auroral observations made from Norway since the earliest time and up to 1878. Tromholt, indeed gave much efforts also to the second work. He compared his collection of auroras with the catalogue, issued by professor Rubenson from Uppsala, on auroras observed in Sweden during 1722–1875, which holds 5529 observations and combined the two to obtain a more solid basis. With this comprehensive material he could improve the statistics on variations in the occurrences of auroras with respect to the locations as well as the season of the year and the solar cycle. The statistics substantiated his former results, among other, the increase in occurrence frequency moving northward in Scandinavia, the equinoctial occurrence maxima and the winter minimum in occurrences of auroras. He examined the solar cycle variations in the frequency of auroras and found, as demonstrated in Fig. 10, a close correspondence between the number of sunspots and the number of nights auroras were observed.

He also noted that the length of the solar cycle has variations not seen in his former work on auroral observations from Greenland extending over the more limited span of years from 1865 to 1879 (Tromholt, 1882a) where the cycle length was found to be 11 yr.

However, since 1892 his health gradually impaired and he, in addition, had great difficulties in providing financial support of himself and his wife, Maria. Continuing auroral research became more and more difficult and he never managed to complete the second work, not even a review like that published in *Pettermann Mittteilungen* for the first work (Tromholt, 1892). Sophus Tromholt died on 14 April 1896 at Dr. Silbersteins Lung Sanatorium at Blankenheim in Thüringen, Germany. His wife survived him by many years and died in 1948 in Baden-Baden, Germany. She left Tromholt's extensive material on observations before 1878 to the renowned Norwegian astronomer Jens Frederik Wilhjelm Schroeter (1857–1927).

Previously, Schroeter collaborated with Tromholt and had, among other, helped him with the comprehensive book on astronomy (Tromholt, 1887a). Since 1892 Schroeter was an observer working for the Astronomical-Geomagnetic Observatory in Christiania and in 1919 he became professor in astronomy at the University. In 1925 he was awarded the Fritjof Nansen's Foundation prize for his excellent book on astronomy.

Jens Schroeter worked up Tromholt's comprehensive material on auroral observations from Norway prior to 1879. The main part is a chronological list of auroral observations made during 1594 to 1878 arranged according to date, phase of the moon, time of the day and location; the source for each observation is noted. For some of the observed auroras selected initially by Tromholt and later by Schroeter there are complete descriptions. In addition the catalogue holds extensive statistical tables on yearly and monthly auroral occurrence frequencies and their distribution over varying geographical latitudes. Tromholts catalogue for Norway is combined with Rubenson's catalogue for Sweden in order to provide a more comprehensive basic material.

Tromholts catalogue of historical auroral observations, further processed by Schroeter, was finally published, posthumous, during 1898–1901 (Tromholt, 1898) with financial support from the Fridtjof Nansen Foundation and the Norwegian Science Academy. Thus, Tromholt's vigorous efforts were finally recognized and rewarded the financial support that he had applied for so often but never obtained during his laborious, vicissitudinous and much too short life.

Acknowledgements. In addition to the above science books and journal articles written by Sophus Tromholt, we have counted from his tireless hand numerous popular books, popular newspaper articles, and travellers letters on various topics spanning from astronomy, geography and expeditions to puzzles with numbers, stick figures, and adventure tales.

Original material, such as correspondence from and to Sophus Tromholt and photos taken by Tromholt have been found at:

The Royal Library, National Library of Denmark, Copenhagen; The National Archives of Norway, Oslo; The National Library of Norway, Oslo; Institute of Theoretical Astrophysics Library, University of Oslo; University of Bergen Library, Bergen; Uppsala University Library, Uppsala.

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