Unravelling the Aurora Borealis*

Nandini Nagarajan

Carl Størmer was a pioneer in the study of the aurora borealis, a mathematician who derived the conditions for the formation of aurora and their trajectories in the atmosphere, making seminal contributions to auroral and space science. He was the first to develop precise photographic methods to calculate the heights and morphologies of diverse auroral forms from observations over four solar cycles (45 years). Størmer independently devised numerical techniques to determine the allowed and forbidden trajectories of high-energy charged particles in the Earth's magnetic field. His theoretical calculations also explained cosmic ray access to the upper atmosphere, 20 years before this was identified by other scientists. His interactions and contributions in the nascent stages of modern geomagnetism are outstanding. The breadth and scope of his theoretical and observational achievements are monumental even by modern standards. His major work, *The Polar Aurora* [1], published in two volumes when he was 81 years old, stands to this day as a valued resource in graduate-level courses on space physics.

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Since the time of Aristotle, observations and explanations of the celestial spectacle of aurora have been attempted; the narrative included a wide spectrum of hypotheses, theories, and speculative suggestions. Electric discharges in aurora were first detected in the late 19th century, and electromagnetic theories were then applied to the study of the aurora, and the aurora was reproduced in laboratory experiments. That was a time of rising interest in the Earth's magnetic field, and diverse approaches to examine phenomena with rigour, combining observation, experiment and theory were attempted.

Keywords
Aurora, geomagnetism, forbidden trajectories, space science, photographic methods, magnetosphere, ring current.

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Fredrik Carl Mulertz Størmer, (1874–1957) was such a pioneer in the study of aurora, evolving a theory of their occurrence, and association with geomagnetic disturbances, and providing insights into the magnetosphere, before the era of space exploration. Developments in photography and the systematic documentation of aurora have earned him undying fame and an honoured place in the pantheon of geoscience. He was educated at the University of Kristiania (Oslo) and Sorbonne, Paris and was appointed Professor of Mathematics at the University of Kristiania in 1903. Størmer showed early promise in the field of mathematics. It is unusual for anyone to publish a paper in the year they enter university as an undergraduate, but this is exactly what Størmer did with a paper on the summation of trigonometric series. He published a series of papers, by the time of the award of his candidate's degree (PhD). Størmer's approach to several mathematical problems were elegant and the results are of wider significance. He presented solutions, in the form of series, for several trigonometric problems. He demonstrated the bounds of several expressions in number theory, involving integers, approximating irrational numbers, etc., and they are widely quoted. He spent several years in France and published collections of work by other mathematicians, in Norwegian and French. He was appointed professor of pure mathematics in 1903 and held the position for 43 years. Details of his work are found in biographies by Chapman [2] and Egeland & Burke [3].

Developments in photography and the systematic documentation of aurora have earned Carl Størmer undying fame and an honoured place in the pantheon of geoscience.

Prof. Kristian Birkeland, at the same University, demonstrated that the Earth's magnetic field would have the effect of pulling electron streams towards the poles, hence similarly affecting a stream of electrons from the Sun, and began his remarkable series of terrella experiments to illustrate and study the phenomenon more thoroughly and these are described in detail by Egeland & Burke [4] (see *Box* 1). These experiments indeed showed that a stream of ionized particles would bombard the sphere around its auroral zones. In the meantime, after Birkeland's first experiments, Poincaré offered an explanation of these results by a mathematical description of the motion of a charged particle in the presence of a single magnetic pole. It appeared from the experiments and the theoretical analysis that a particle, say from the Sun, incident on the geomagnetic field might be guided in by the lines of force and strike the atmosphere, thus inducing the optical display. Birkeland proposed that electrons from the Sun, with high energies, were deflected towards the poles. These results diverted Størmer's interest toward aurora, and he worked on the mathematical formulation of conditions to explain Birkeland's results and their significance. He then concentrated on the electrodynamic problem of the motion of a charged particle in the field of a dipole, which approximated the Earth's magnetic field sufficiently and might give a good explanation of observed auroral trajectories.

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Theoretical Contributions to the Study of Aurora

Størmer began to work on deriving trajectories of charged particles in magnetic fields. An important result was the formulation to calculate trajectories in a dipole magnetic field, published in 1907. He found integral solutions for particles moving in a static magnetic field. For a complete analytical solution of the problem, three integrals of motion were to be formulated, obeying the law of conservation of generalized angular momentum of a particle that follows from the isotropy of space (see *Box* 2 on Størmer's equations). As this was a difficult problem to solve using manual numerical integration, he used several simplifying assumptions: only the terrestrial dipole magnetic field acts on the particles, and geometry was reduced to axial symmetry. Størmer solved this simplified problem by obtaining an expression for a special parameter that determined the geometry of allowed and forbidden regions of motion for a charged particle.

Størmer found integral solutions for particles moving in a static magnetic field.

Box 1. Aurora and Terrella

Aurora is a natural electrical phenomenon characterized by the appearance of streamers of reddish or greenish light in the sky, especially near the northern or southern geomagnetic pole. The effect is caused by the interaction of charged particles from the Sun with atoms in the upper atmosphere. In northern and southern regions, it is respectively called *aurora borealis* or northern lights and *aurora australis* or southern lights. Aurora are the result of disturbances in the magnetosphere caused by the solar wind. These disturbances are regularly strong enough to alter the trajectories of charged particles in both solar wind and magnetospheric plasma. These particles, mainly electrons and protons, precipitate into the upper atmosphere. (thermosphere/exosphere). The resulting ionization and excitation of atmospheric constituents emit light of varying colour and complexity. For more information, see [5].

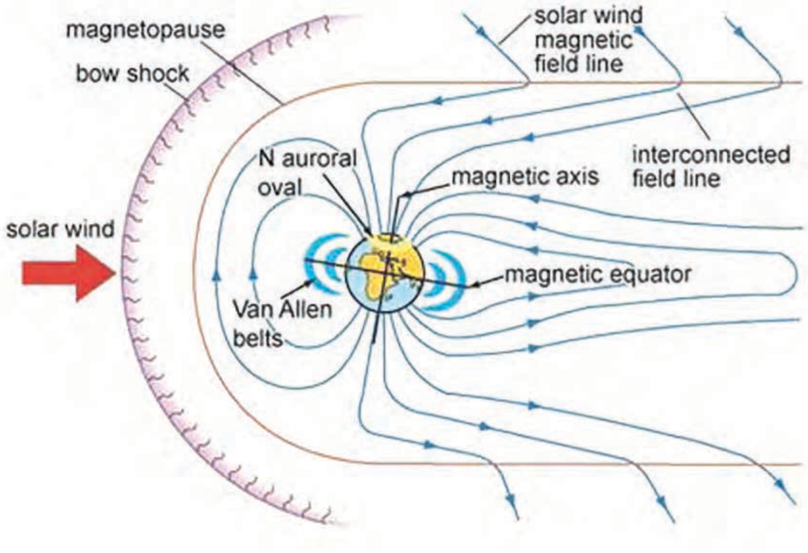

Figure A. The structure of the Earth's magnetic field.
(Source: Physics World, The Mysterious Aurora. http://www.hk-phy.org/iq/aurora/aurora_e.html)

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Box 1. ***Contd.***

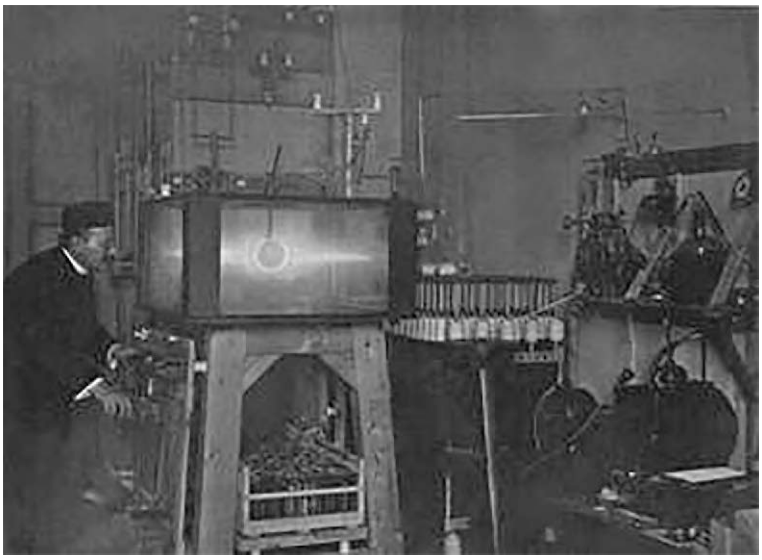

Figure B. Kristian Birkeland and his terrella experiment. (Source: Wikimedia Commons)

A *terrella* (Latin for "little Earth") is a small magnetised model ball representing the Earth that is thought to have been invented by the English physician William Gilbert while investigating magnetism. It was further developed 300 years later by the Norwegian scientist and explorer Kristian Birkeland to demonstrate magnetic effects in the atmosphere.

Box 2. Some Dynamical Lessons from Størmer's Forbidden Regions

One of the important results from Størmer's work is the existence of allowed and forbidden regions which restrict the orbit of a charged particle in the Earth's magnetic field, which one can determine from the initial conditions without solving for the whole orbit. Here, we outline how the existence of these regions follows from the dynamics. A forbidden region is, of course, nothing new.

A particle moving in one dimension, with a conserved energy $E = \frac{mv^2}{2} + V(x)$ can only access values of x where the total energy E exceeds the potential $V(x)$. The situation is more subtle for a charged particle moving in a magnetic field. Magnetic fields are 'lazy'—they do no work. The Lorentz force $\boldsymbol{F} = q(v \times \boldsymbol{B})$ is perpendicular to the velocity v. The kinetic energy $K = \frac{mv^2}{2}$ is, therefore, a constant. The magnetic field is described by a vector potential, $\boldsymbol{A}$, related to the field by $\boldsymbol{B} = \triangledown \times \boldsymbol{A}$. Apart from the kinetic energy, one more constant is provided by the angular momentum about the axis of the dipole since there is symmetry with respect to rotation about that axis (see the *Resonance* issue on Emmy Noether, September 1998, for more on the relation between symmetry and conservation laws). The force due to a dipole magnetic field on a charge moving with a radial velocity, for example, towards the axis, will have a component in the tangential direction and hence produce a torque. This means the usual angular momentum $r \times mv$ is not conserved. However, a modified angular momentum, which is not just $r \times mv$ but includes an additional term proportional to $\boldsymbol{A}$, is conserved. Størmer discovered this directly as an integral (conserved quantity) from his equations of motion. These two conservation laws are seen to restrict the orbit to allowed spatial regions whose shape depends on the initial conditions. The calculations for a dipole field are revisited, somewhat unusually, in an obituary by Chapman [2].

Størmer's equations have been applied to more complex fields as well [6]. The figures reproduced below are from this work. They illustrate both the orbits and the allowed/forbidden regions. Note that the figures are plotted in cylindrical coordinates; z is along the dipole axis, and ρ is the distance from that axis, i.e. $\rho = \sqrt{x^2 + y^2}$. The third coordinate, φ, which is the usual polar angle in the x-y plane, is suppressed, but the particle does move in this direction, as well, since it has angular momentum about the z-axis. *Figure* C shows the case where the particle comes in from infinity and has two kinds of allowed paths: back and forth in a crescent-shaped region extending from pole to pole and also the path going back to infinity. The latter is appropriate in the case of a cosmic ray particle being deflected without reaching the Earth. Note that the axis of the dipole is horizontal in the figures (from [6]).

Figure D shows another kind of orbit—a charged particle trapped in a crescent shaped region without an escape route, bouncing from pole to pole. The region looks like a crescent in section but the full, accessible region is obtained by rotating about the axis, and forms a kind of thick belt girdling the earth, perpendicular to the dipole axis (which does not coincide with the earth's rotation axis). These are the famous Van Allen belts, filled with a high concentration of energetic charged particles, which were discovered when spacecraft were first sent high enough to explore these regions. The particles can damage equipment, so avoiding the belts is an important consideration in planning satellite/space missions (from [6]).

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Box 1. ***Contd.***

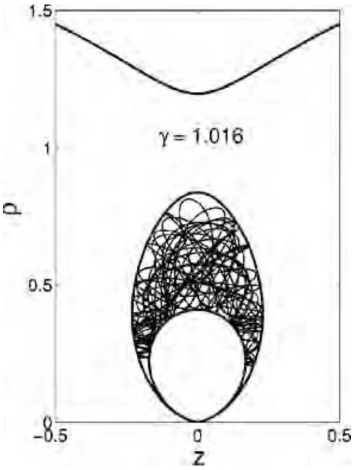

Figure C: The figure shows the motion in the *ρ*–*z* plane for a particle coming from infinity into a dipole field (Reproduced from J V Shebalin, Størmer regions for axisymmetric magnetic multipole fields, *Physics of Plasmas*, Vol.11, No.7, pp.3472–3482, 2004, with the permission of AIP Publishing. [6]). The parameter γ is defined in the paper and determines the topology of the allowed region.

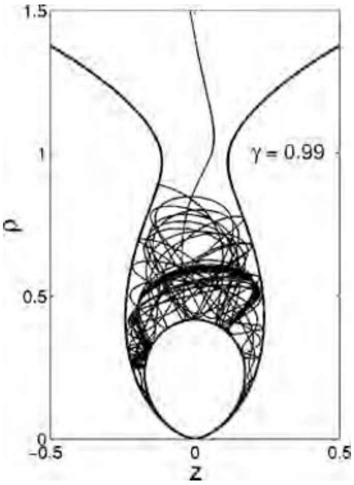

Figure D: The figure shows a motion of a particle trapped in a belt surrounding the Earth, in *ρ*–*z* plane for a dipole field, for $\gamma = 0.99$ (Reproduced from J V Shebalin, Størmer regions for axisymmetric magnetic multipole fields, *Physics of Plasmas*, Vol.11, No.7, pp.3472–3482, 2004, with the permission of AIP Publishing. [6]).

Størmer obtained the boundaries of the allowed regions of motion for particles coming toward Earth from infinity. These have been illustrated with simulations and extended further more recently.

As a result, Størmer obtained the boundaries of the allowed regions of motion for particles coming toward Earth from infinity. These have been illustrated with simulations and extended further more recently [6–8]. However, at that point in time, more realistic solutions required numerical solutions. These calculations form a major part of his work and that of his assistants. In the process of doing so, several discussions by correspondence were held with his contemporaries (we need to remember that journeys were made by sea, and even letters took weeks to be answered; publication of major work could sometimes even take 20 years!)

He made elegant transformations that made the calculation of trajectories easier in the era of hand computations. His work on trajectories defined surfaces bounding forbidden and permitted regions. These were all surfaces about the polar axis, creating oval zones. Later, global observations have indeed shown that auroral ovals do form, and they shift in latitude, poleward or equatorward, depending on the intensity of magnetic disturbances. These findings were published in a series of papers in French, Norwegian and German, and therefore, it is not easy to access most of his original work. His work has been summarized in some biographical notes [2, 3] and quoted in more recent papers that are easily accessible (most of Størmer's early work is not, nor are his important books: *Polar Aurora* [1], *Photographic Atlas of Aurora* [9]).

He extended his work to propose a ring of electrons orbiting the Earth, growing stronger with magnetic disturbance. This is the 'Størmer ring current'. A retrospective view of his work states: "The ring current is one of the oldest concepts in magnetospheric physics, yet still one of the most poorly understood". The proposal of a ring of current encircling the magneto-sphere was first introduced by Størmer in 1911 and given additional support by Schmidt in 1917. A ring current was later used in the model of the geomagnetic storm presented in a series of papers by Chapman and Ferraro between 1931 and 1941 [10].

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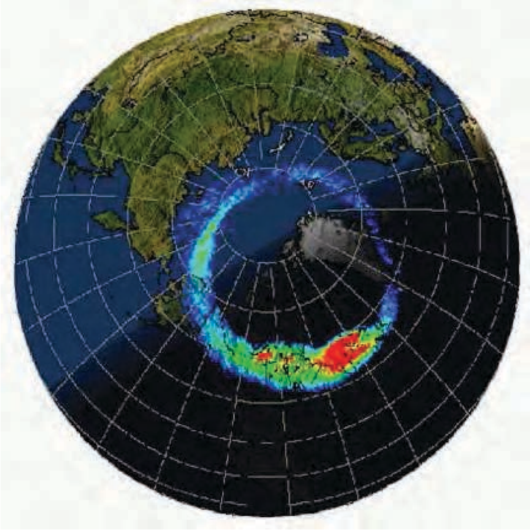

Figure 1. Formation of an auroral oval around the geomagnetic pole, as deduced from Stormer's derivations, photographed from space. (Source: NASA, https://www.nasa.gov/sites/default/files/images/147514main_oval_in_dark.gif)

charged particles (electrons) moving from the Sun to the Earth. The geometry of the Earth's magnetosphere, the existence of radiation belts, the composition of the interplanetary magnetic field, etc. (see *Box* 1), were, however, established through direct observations only in the 1970s.

The result of Størmer's analysis was the definition of allowed orbits/trajectories in the Earth's polar regions and also the forbidden regions. The observations of the auroral ovals (*Figure* 1), and their widening and shrinking, validate his calculations and theories. Today, maps of the real-time auroral ovals obtained from all-sky observations, and photographs from satellites, and yes, even by astronauts in the International Space Station, are readily accessible in the public domain (see [11]).

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A severe test of his theories came from observations that the limiting zone derived for cathode rays and protons (ions) was too close to the poles (higher latitudes) than actually observed. It must be noted that the configuration of the Earth's magnetosphere and the properties of the interplanetary magnetic field (IMF) were not definitely known till the era of space exploration began in 1958.

Photography and Classification of Aurora

An important aspect of Størmer's work was the decades-long study of the aurora from field observations—from 1909 until 1956. He sought to understand the phenomenon thoroughly through detailed observations. Although aurora was first photographed in 1892, Størmer was the first to undertake a systematic scientific photographic investigation which he began in 1909 and continued throughout his career. Several campaigns to photograph aurora were carried out, with Størmer himself participating along with trained assistants near the Arctic Circle. The Government of Norway funded this long drawn out program and also set up special telephone lines for the observers to communicate with each other from their remote observation posts. Photographs were also taken at night, in sub-zero temperatures (*Figure* 2).

Although aurora was first photographed in 1892, Størmer was the first to undertake a systematic scientific photographic investigation which he began in 1909 and continued throughout his career.

He compiled an unparalleled dossier of photographs of aurora and used these photographs to classify them, determine their heights, spectra, etc. An example of those early photographs is in *Figure* 3. The compendium is the most authoritative work on aurora and has been used as a database to study the development of aurora, as well as validate evolving theories of their occurrence. The scope of this study and the concerted efforts involved can be gauged from the 40,000 auroral photographs that make up the database. From 1911 to his last years, Størmer continued this parallactic photography in southern Norway. He amassed more than 9000 sets of pictures, from which he derived the heights and locations of more than 18,000 auroral events. Apart from the nocturnal effort involved in getting the photographs, their reduction was herculean labour, in which Størmer showed the same perseverance and tenacity as he manifested in his theoretical work.

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Størmer was the first to establish beyond doubt the height of the aurora. He provided valuable statistical analyses and diagrams that summed up the results of his observations; these (and similar research by others) are described in his monumental work *The Polar Aurora* [1]. His work stimulated others in different parts of the Earth to observe and calculate auroral heights and positions—

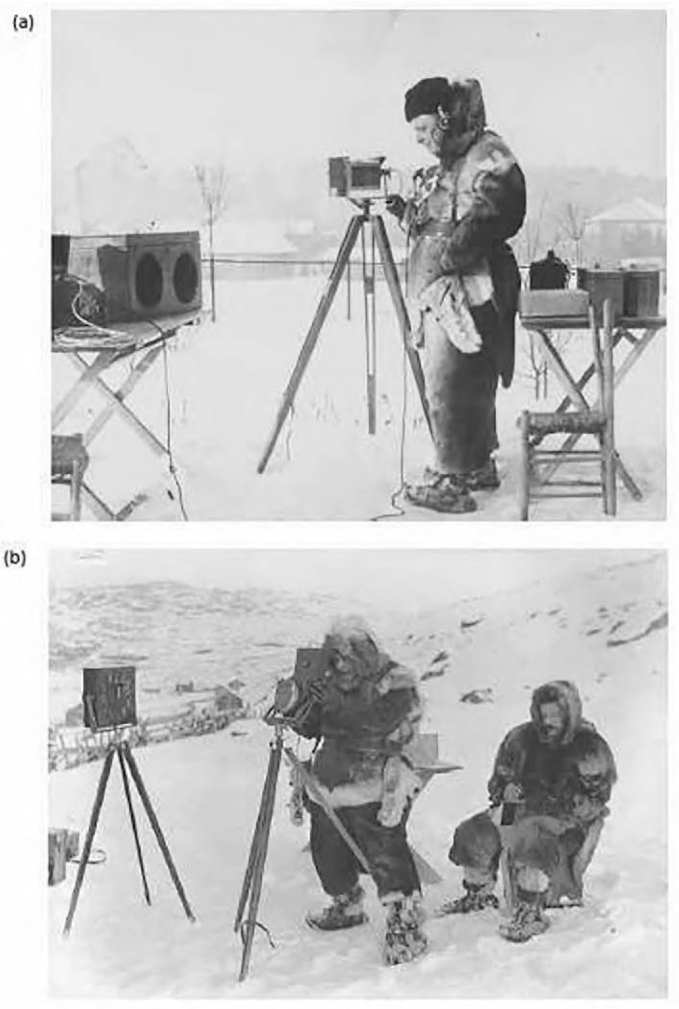

Figure 2. **(a)** A photograph from Størmer's campaigns to observe the aurora in Arctic Norway. **(b)** Størmer and Birkeland together, in the Arctic. (Source: The National Library of Norway–Nasjonalbiblioteket).

notably during the Second International Polar Year. He actively encouraged and helpfully advised others who took up such work for many decades. However, it is remarkable that none of his papers bears any name other than his own, though their text often refers to contributions by his assistants, to their methods or ideas; some of those contributions were substantial! Perhaps this is a reflection on the mores of those times.

Photography, at night, of distant atmospheric lights was a technical challenge in the 1900s. Størmer's early interest in field ob-

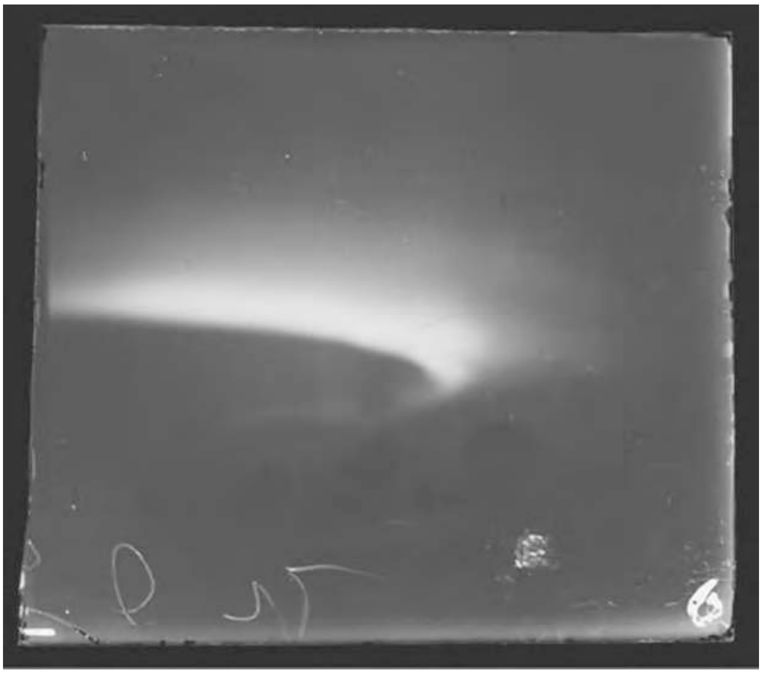

Figure 3. Reproduction of a black and white image of aurora captured with a photographic plate-mounted camera, 1930 in Finnmark, Norway. (Source: The National Library of Norway–Nasjonalbiblioteket)

servations (botany) and photography, combined with his rigorous approach, led to several innovations in photography. A quote from the preface of his book [1], "...found it necessary to obtain more facts about the aurora in order to compare theory and observation. A photographic method designed to determine, among other things, the height and position of aurora was therefore developed and successfully applied. The chief results obtained from the analysis of a vast number of parallactic photographs are discussed in this book". The body of Størmer's work was published in this book [1] in two volumes. Descriptions of these campaigns can be found in the book and also in articles on the history of science. The invaluable body of photographs of aurora, their classification by altitude, spectrum, pulsing, etc., was the foundation for the quantitative study of aurora for the next 50 years. Though it is difficult to obtain his books, several detailed reviews and historical articles provide valuable information. The observations, derivations and inferences therein are a testament to Størmer's

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mastery over both theory and observation. His theoretical works were published and debated contemporaneously with other scientists between 1910 and 1940. Though many theories developed by Størmer have been found inapplicable to newer, more recent observations, his book presents an unrivalled and authoritative compendium of observations of aurora, made using groundbreaking techniques in photography. In addition, it also included descriptions of radio echoes recorded from aurora.

Photography of aurora on the ground and from space has developed rapidly with special equipment and processing techniques; examples of modern photography are given in *Figure* 4. The structure of aurora, observed over a wider spectrum and in greater detail, provides more constraints on theories of particle interactions and atmospheric processes. Photography from spacecraft, using visible and ultraviolet imagers, has provided clear images of the planetary aurora, mostly from the giant planets, Jupiter and Saturn (*Figure* 5 (a) and (b)). Recently, auroras have been detected on Mars and Venus. Apart from producing stunning images, the significance of these auroras lies in the modelling of magnetic fields in near-space and around the planets and the interaction of planetary atmospheres with the solar wind. In theory, aurora could occur on some kinds of stars, too, and early observations have been made.

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Applications of Størmer's Work

Størmer's wide-ranging understanding of both observation and theory led to the establishment of other significant facets of natural electromagnetic phenomena. His work formed the basis of synoptic auroral studies, involving active collaboration across continents, and this formed the basis for the International Polar Years.

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In his book on aurora, he further described the properties of auroral forms, classified by colour and shape, and special and sunlit aurora. The occurrence of aurora at great heights was established by photographing aurora persisting in the sunlit sky.

Some important aspects of Størmer's theoretical work included

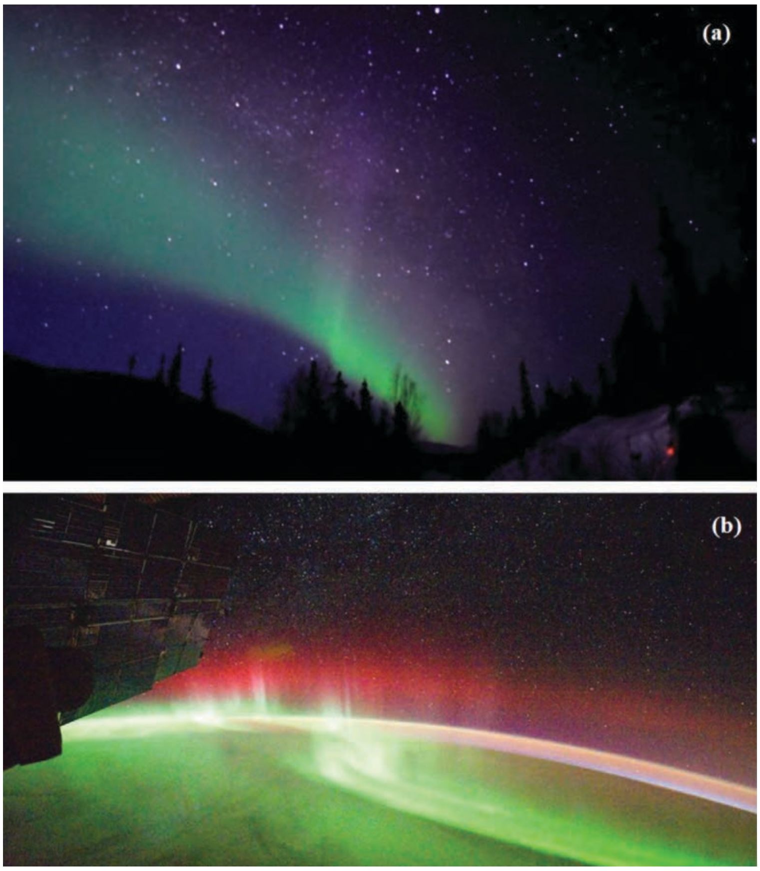

Figure 4. Spectacular auroral displays are photographed, both on the ground and in space, using advanced techniques accessible to trained observers and citizen scientists. **(a)** Aurora observed from the ground at Chena Hot Springs, Alaska, 2013 (Source: LCDR Gary Barone, NOAA Corps (ret.), photographer. NOAA Photo Library); **(b)** Image of aurora australis (southern lights), as observed from ISS (Source: NASA).

trajectories of ions as well and paved the way to understand other important phenomena: pulsations seen in magnetic variation records, generation and detection of cosmic rays, etc. He contributed to the contemporary understanding of magnetic pulsations by applying his mathematical derivations. These findings were published in 1932. Another development stemming from Størmer's work on the trajectories was the growth of interest in cosmic rays among many physicists.

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Other Luminous Phenomena of the Atmosphere

Other interesting luminosities in the atmosphere were also recorded during these auroral observing campaigns. Among these were

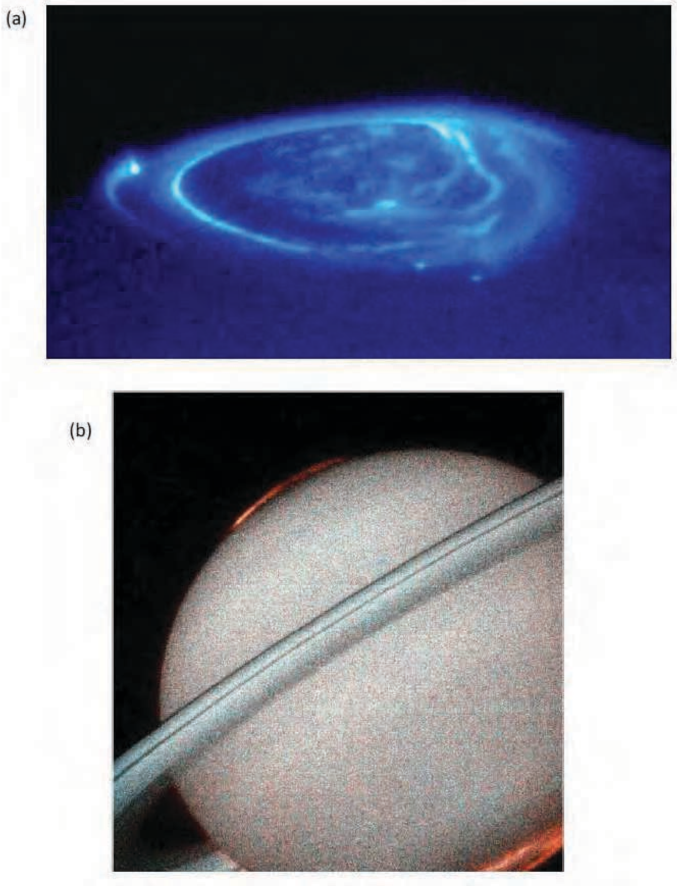

Figure 5. Ultraviolet imaging of aurora on giant planets. **(a)** Jupiter, close-up view of an electric-blue aurora that is eerily glowing one half billion miles away on the giant planet Jupiter in 2010 (Source: Hubble Space Telescope); **(b)** Aurora over Saturn (Source: Hubble Space Telescope, NASA/ESA/Hubble).

two kinds of cloud formations occurring at unusual heights in the atmosphere—nacreous and noctilucent clouds were studied and classified, and several papers were published on the subject. He applied his formulation to determine auroral heights to the measurement of the heights of these clouds and proved that they lie in the stratosphere, at heights from 21 to 30 km, well above the tropopause. They are thought to be formed of super-cooled water drops. They show beautiful iridescent colours, and in 1948, he presented colour photographs of them to the International Association of Meteorology meeting in Oslo.

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Developments in Geomagnetism

Størmer's work is not regarded as the cornerstone of modern geomagnetism because he initially developed trajectories of only electron streams, simplifying geometries and solar ion streams. During 1910–1930, there were several concurrent developments in the study of geomagnetism. Identifying magnetic storms as a global phenomenon, collating records from different observatories, formulation of a theory to explain their common characteristics and significantly linking storms to solar disturbances and the mechanisms of transport from the Sun slowly gathered momentum, and theories that were developed in isolation had to be modified to resolve inconsistencies and accommodate new observations. Concurrent, seminal work by Chapman and Ferraro on the formation of a ring current to explain magnetic storms, however, gained wider recognition and has stood the test of more recent observations [12, 13].

Størmer's lasting contributions were the development of mathematical formulations that circumvented laborious hand calculations and provided quick and approximate calculations of trajectories in diverse conditions.

Størmer's lasting contributions were the development of mathematical formulations that circumvented laborious hand calculations and provided quick and approximate calculations of trajectories in diverse conditions. This prompted several others to make similar attempts and sparked quantitative testing of possible trajectories in more complex magnetic fields [8]. His formulations are applied to present-day modelling of trapped radiation in the Earth's near-space (Van Allen belts); distribution of particles during disturbances (that would seriously impact the health of satellite missions); interplanetary plasma; solar and stellar magnetic fields; behaviour of ions in superposed dipole and quadrupole fields. The last also extends to more realistic studies of magnetic field reversals [6–8]. Størmer equations are also used to estimate the bounds of particle trajectories in the multipole inter-galactic environment. His research papers were written in four languages, across multiple journals that are not easily accessible. However, retrospective commentaries and extensions of his work are available and are referenced here.

His work stimulated others in different parts of the world to observe and calculate auroral heights and positions—notably during the Second International Polar Year. He actively encouraged and helpfully advised others who took up such work; for many decades, he was the acknowledged leader among auroral observers. He long acted as the Chairman of the Auroral Committee of the International Association of Terrestrial Magnetism and Electricity (now the International Association of Geomagnetism and Aeronomy) of the International Union of Geodesy and Geophysics. In this capacity, he prepared a valuable Photographic Atlas of auroral forms (and later, a Supplement in 1930), giving a classification of forms derived from numerous photographs by himself and his assistants; it also described methods of photographic and visual observation of aurora. He was the President of the Auroral Committee for the Second International Polar Year 1932/33.

It is interesting to note that a professor of pure mathematics at Oslo University continued to receive funding and support for these outdoor observations, extending over decades. It would be hard to envisage individual researchers having such a free hand to conduct interdisciplinary research over such a length of time today. Both Nansen and Amundsen, pioneers of polar sea-faring exploration, were supported by the Norwegian public and the Government during 1890–1930. It speaks for the prevailing attitudes towards science in contemporary Norway.

It is interesting to note that a professor of pure mathematics at Oslo University continued to receive funding and support for these outdoor observations, extending over decades.

Under a portrait of Gauss, at the Royal Astronomical Society in London, there are the following words, from Shakespeare's *King Lear*: " ...Thou Nature art my goddess, To thy service, I am bound." Sidney Chapman, a contemporary, paid tribute to Størmer thus: "These words are as applicable to Størmer as to Gauss. Throughout his long life, Størmer pursued his chosen course of observing Nature and applying his fine intellect to the unravelling of some of its mysteries."

Acknowledgement

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Norwegians in the National Library of Norway, proved a very good resource.

Note: Though some important work of Størmer has been cited, most of it is inaccessible. Biographies, and reviews are the main sources.

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