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COMMENTARY
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**Key Points:**
- Carl Størmer reported on observations of subauroral arcs, interpreted as STEVE arcs, for seven individual days between 1911 and 1940
- Carl Størmer reported on height measurements for subauroral arcs, interpreted as STEVE arcs, ranging from 138 to 259 km
- Størmer's and earlier descriptions of subauroral arcs by Bond et al. (1889), interpreted as STEVE arcs, indicate unusual spectra

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# Early Ground-Based Work by Auroral Pioneer Carl Størmer on the High-Altitude Detached Subauroral Arcs Now Known as "STEVE"

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**Abstract** STEVE (Strong Thermal Emission Velocity Enhancement) phenomenon related structures have received much attention from space weather audiences in recent years. MacDonald et al. (2018, https://doi.org/10.1126/sciadv.aaq0030), reports on a link between these ionospheric structures and the subauroral ion drift for the first time. This commentary summarizes previously overlooked observations of a distinct type of detached subauroral arc by the aurora pioneer Carl Størmer in Norway between 1911 and 1940, including coordinated simultaneous multistation-based altitude measurements. This commentary points out that his phenomenological descriptions and height measurements show a striking resemblance to modern descriptions and measurements of STEVE.

**Plain Language Summary** Discussions by the amateur aurora observer community with the citizen science project Aurorasaurus and the scientific community initiated the discovery of the significance of seemingly new aurora or aurora-like structures. They occur detached, toward the equator, from the auroral ovals. They are linked to atypically high ion temperatures and velocities in the subauroral ion drift, a narrow ionospheric structure with an extended east-west structure. MacDonald et al. (2018) describe these structures for the first time in the modern literature and have introduced the term STEVE (Strong Thermal Emission Velocity Enhancement) for the phenomenon. Little known today are the early observations and measurements of the aurora pioneer Carl Størmer on a distinct type of aurora-like arc observed detached, toward the equator, from the main zone of aurora activity, and mostly published in lesser known journals in the 1930s and 1940s. Størmer and his team were able to determine the unusually high heights of these structures. This commentary shows that his descriptions and height measurements show a striking resemblance to modern descriptions of STEVE. Størmer's work is an example that shows these early publications can still contribute to topics of high interest in the space weather field today.

## 1. Introduction

A seemingly new ionospheric structure has received much attention in recent years. MacDonald et al. (2018) introduced the term STEVE (Strong Thermal Emission Velocity Enhancement), previously proposed by Chris Ratzlaff from the Alberta Aurora Chasers, for this distinct class of subauroral aurora or aurora-like structures. Their work verifies for the first time a link between these structures and SAIDs (subauroral ion drifts). Follow-on publications confirm and extend this finding (Archer, Gallardo-Lacourt, et al., 2019; Chu et al., 2019; Gallardo-Lacourt, Liang, et al., 2018, Gallardo-Lacourt, Nishimura, et al., 2018; Nishimura et al., 2019). Key optical STEVE characteristics include an extended narrow structure flowing from east to west horizons that appears faint and colorless to the naked eye but mauve or white in modern color photography. This subauroral structure only happens when there is some aurora separated poleward, is most apparent in the zenith, lasts on the order of an hour, and generally occurs before local magnetic midnight. Sometimes, the STEVE structure is accompanied by narrow "picket fence-like" rays that are green in modern color photography and nearly invisible to the naked eye due to their ephemeral nature lasting only seconds or minutes. Spectroscopic measurements reveal a spectral composition atypical of aurora for STEVE arcs (Gillies et al., 2019; Liang et al., 2019). Unlike typical aurora, STEVE arcs show a broadband emission spanning from ~ 400 to 730 nm (Gillies et al., 2019) superimposed by red line emissions at 630 and 636.4 nm (Liang et al., 2019) in their upper region. It is important to note that only few STEVE spectra are published in the modern literature and that the research on this topic is ongoing. The green aurora line at 5,577 Å dominates the reported "picket fence" spectra (Gillies et al., 2019; Liang et al., 2019; Mende et al., 2019). According to Mende et al. (2019) reported "picket fence" spectra also contain N1 first positive (1P) emissions at ~ 640 to 760 nm. STEVE arcs show distinct characteristics allowing a clear identification in naked-eye and camera-documented observations.

Carl Størmer was one of the great aurora pioneers in the first half of the twentieth century. His enormous body of work included calculating trajectories for charged particles in the Earth's magnetic field, introducing the concept of the ring current, developing the first aurora camera able to work with a few seconds of exposure time, and being the first who conducted reliable aurora height measurements using a network of aurora observation stations in Norway. He classified the different forms of observed aurorae and prepared the first atlas of auroral forms (Størmer, 1930). Størmer's work was groundbreaking for aurora research at his time, both his new theoretical concepts and his careful experimental work. For a more detailed study of his work on polar lights Størmer's book *The Polar Aurora* (Størmer, 1955) and the biography *Carl Størmer—Auroral Pioneer* from Egeland and Burke (2013) are essential. A biography published by Chapman in 1958 includes an extensive list of his publications (Chapman, 1958). This commentary focuses on his observations of what is recently known as the STEVE arc, in total only a very minor part of his extensive work on the aurora.

Størmer's early contributions to the research on what is now known as the STEVE phenomenon are largely unknown. Over multiple solar cycles and many campaigns he and his assistants had a few rare opportunities to study it. Using an extensive state-of-the-art network of aurora observation stations in Norway, Størmer and his team measured the height of the aurora in simultaneous and coordinated observations from 1911 to 1944. Størmer has published three monographs that present detailed descriptions including form, color, dynamic, and location for "Remarkable aurora-forms from Southern Norway" observed from his extensive network (Størmer, 1935; Størmer, 1936; Størmer, 1942). Among these specific forms is a type called "feeble homogeneous arcs of great altitude." Størmer describes these arcs with distinct characteristics: faint to the naked eye, clearly detached (toward the equator) from the main zone of aurora activity, well defined in their latitudinal extent (both equatorward and poleward boundaries are not diffuse), E-W oriented, observed close to the zenith. Størmer describes them as nearly steady in form with slow or no apparent southward drift. The available knowledge in the prespace era and technical limitations did not allow in situ observations; therefore, SAIDs were not known in Størmer's time. Størmer classified "feeble homogeneous arcs of great altitude" as a distinct and rare form of aurora.

Størmer published his results prior to the substantial breakthroughs in aurora research caused by the International Geophysical Year (IGY) 1957–1958 and mainly in lesser known (though available online) journals like the Norwegian journal Geofysiske Publiskasjoner. After the IGY and the beginning of space-based observations, the field focused extensively on substorm phenomena; many rare subauroral phenomena have been understudied. In addition Størmer's publications span, at least, five languages (Dutch, English, French, German, and Norwegian). Størmer's observations include remarkably clear and consistent descriptions with modern descriptions of STEVE arcs in terms of the optical appearance, location, behavior, form, motion, height, and spectral characteristics, limited by the number of observations and availability of equipment to observe and record the spectra.

## 2. Early Descriptions and Altitude Measurements by Størmer

According to Størmer (1935) "feeble homogeneous arcs of great altitude" were very rare in southern Norway at the time of his observation campaigns: "… there occurs in Oslo on rare occasions another type, which consists of a thin sharply limited homogeneous arc, some degree wide and with very feeble luminosity. This arc is, in general, situated near zenith, lasts from half to about one hour, and during its appearance is far from other aurorae, which, if any, occur only near the northern horizon. The height of these remarkable arcs is about twice that of the height of the common arcs mentioned above … ."

In total, Størmer reports on seven of his own observations. Table 1 summarizes his observations. Størmer published his early work on these distinct arcs in Dutch (Størmer, 1911), French (Størmer, 1912), and German (Størmer, 1931). In all of these, he reports on an observation from 22 February 1911, including height results and few details; see Table 1 and section 4. His monograph Størmer (1935) fully focuses on "feeble homogeneous arcs of great altitude" and is his main work on these arcs. It presents extensive

**Table 1**
*"Feeble Homogeneous Arcs of Great Altitude" Observed by Størmer's Aurora Observation Network in Southern Norway*

| Day, time (UTC), duration | Height (min/mean/max) (km), if two heights are listed the first is the lower edge, and the second the upper edge | Number of stations | Reference points | Reported details | References |
|---|---|---|---|---|---|
| 22 February 1911, 19:50, 1 hr | 159/177/196 | 2 | 6 | Stretched over the whole sky from horizon to horizon, from St. Petersburg to west of Scotland, if an equal height is assumed (Størmer, 1911), weak luminosity in the blue and near-UV spectral range (Størmer, 1912), thin homogeneous band, a few degrees wide, from east to west, visible for 1 hr without movement, detached from activity at the northern horizon (Størmer, 1931) | Størmer (1911, 1912, 1931, 1935, 1955) |
| 29 September 1930, ~9:00, ~30 min | 170/195/227<br>214/232/272 | 3 | 13 | Near zenith, no spectral line visible with pocket spectrosope, although visible in faint aurora glow at the horizon later, very feeble, detached from feeble glow on north horizon, detailed eye witness reports, reported with sketches and photos (Størmer, 1935) | Størmer (1931, 1935, 1955) |
| 10 March 1932, 20:50, 39 min | 163/192/230<br>215/227/259 | 3 | 17 | Very faint, height near zenith, a narrow completely steady stripe, detailed eye witness reports, at the same moment the high arc disappeared aurora with rays appeared near the northern horizon, reported with sketches and photos (Størmer, 1935) | Størmer (1935, 1955) |
| 9 December 1933, 21:55, 20 min | 194/197/199<br>210/216.5/226.5 | 3 | 5 | It looked like a ray or comet's tail and stood quite isolated and far more south than the aurora seen earlier from which pulsating patches near the northern horizon remained, detailed eye witness reports, at the same moment the high arc disappeared aurora with rays appeared near the northern horizon, reported with sketches and photos (Størmer, 1935) | Størmer (1935, 1955) |
| 6 February 1938, 19:30, 16 min | 138/159/181 | 3 | 24 | Arc in Earth shadow, well separated from the rest of the aurora, very similar to arcs observed in 1930, 1932, and 1933 (Størmer, 1939) | Størmer (1939, 1942, 1955) |
| 5 March 1938, 20:32, 24 min | 172/183/195[a] | 5 | 7[b] | Details as reported for 6 February 1938, reported with photo (Størmer, 1939), reported with spectrum (Størmer, 1939, 1942) | Størmer (1939, 1942, 1955) |
| 20 December 1940, 17:09, 35 min | ~200[b] | 3 | 24 | Similar arc as observed in 1930, 1932, and 1933 (Størmer, 1955) | Størmer (1942, 1955) |

[a]In total, 49 single heights with an average of 178 km; listed heights for this observation are for the longest baseline. [b]Photos only partially analyzed according to Størmer (1942).

phenomenological descriptions, eyewitness reports, height measurements for three observations (see Table 1), and a few references to earlier observations. He also briefly mentions his observation from 1911. Størmer (1939) describes his auroral work in Southern Norway in the year 1938 and reports on, besides other observations, two observations of these distinct type of arc (see Table 1). These two arcs were situated in the Earth shadow thus excluding a characterization as sunlit aurora. Sunlit aurorae are reported with very high reaching rayed structures (up to >1,000 km) occurring within the auroral ovals (Størmer, 1955). His monograph Størmer (1942) mainly gives detailed descriptions for other specific aurora forms: pulsating surfaces, flaming and flashing aurorae, certain cloudlike aurorae, divided rays, red patches and red arcs, remarkable sunlit aurora rays, and isolated pulsating arcs (and patches). The isolated pulsating arcs were observed

**Figure 1.** Carl Størmer's published work includes photography of "feeble homogeneous arcs of great altitude" for four individual days. This photo shows the arc photographed by Størmer's team on 9 December 1933. (Reprinted with permission from Geofysiske Publiskasjoner).

detached from the main zone, toward the equator, of aurora activity. It also includes observations of "feeble homogeneous arcs of great altitude" earlier reported in Størmer (1939) and another one from 1940 (see Table 1 ). In his last major work on aurora, *The Polar Aurora* (Størmer, 1955, pp. 96–97), he presents a brief summary of his own observations of these distinctive high-altitude arcs in the context of an extensive overview about altitude measurements for 12,330 aurorae classified into many different types. It is clear from his very detailed descriptions of auroral forms that he was fully aware of the distinct nature of "feeble homogeneous arcs of great altitude" and the phenomenological differences between them and other specific forms, for example, sunlit rays or isolated pulsating arcs.

Størmer (1935) reports on height results for the lower and upper edges of the observed arcs. Other publications (see Table 1) report height values without referring to the upper or lower edge. Chapters IV and V of his book *The Polar Aurora* (Størmer, 1955) describe in detail the method applied for height measurements. Two of his publications (see Table 1) present the first known published black and white photos of these arcs; one image is reproduced in Figure 1. Størmer's team took photos on all days for the height calculations. However, Størmer did not publish them for all observations. Størmer's height results are in good agreement with the first results published in the modern literature by Archer, St.- Maurice, et al. (2019). According to Archer et al., a STEVE arc observed on 16 September 2017 had an altitude range of between 130 and 270 km.

Størmer suggested in newspapers and by radio that observers should send him observation reports and used this amateur data as an integral part of his research similar to the ongoing Aurorasaurus project. Aurorasaurus aims to implement amateur observations and the methodology of citizen science into the current auroral research process in a rigorous and useful manner (MacDonald et al., 2015).

Earlier attempts to measure the height of aurorae, for example, that reported by Dalton (1828) leading to an altitude of ~160 km for an aurora-like arc, detached from the auroral oval and interpreted as a STEVE arc, were less successful or accurate because of the lack of available techniques allowing coordinated, simultaneous observations. Techniques available at the time of Størmer's pioneering aurora altitude measurements, utilizing telephone networks, allowed such coordinated simultaneous observations through his ingenuity and dedication.

## 3. Observations by Other Observers Mentioned by Størmer

Størmer (1911, 1912) both report on a further observation from Sweden for 21 February 1911, not discussed in his later works. In Størmer (1935) he states: "Probably similar arcs have been observed in other countries from time to time. I have not had occasion to look into such observations … ." He only lists four older observations from Norway, collected by Sophus Tromholt (6 October 1847, 15 February 1858, 15 February 1865, and 12 February 1867) and mentions one further from Sweden, observed on 2 January 1897 and previously reported by Bohlin (1898), and one for 13 September 1933 observed from Norway and Great Britain. Bailey et al. (2018) presents a first summary of potential historical observations of STEVE structures, all earlier than Størmer's observations. Hunnekuhl (2019) presents an extended list of historical STEVE candidates. A classification scheme for the variety of STEVE structures would ease the identification of potential historical observations and make them more reliable. Amateur observer and citizen science data are of fundamental importance to create such a scheme.

It is possible that Størmer did not carry out any detailed literature research to search for older observations of "feeble homogeneous arcs of great altitude." In his book *The Polar Aurora* he refers only to Geddes (1939). Geddes reports on a comparable isolated arc observed in New Zealand on 15 September 1938 and another one reported from Macquarie Island in the Southern Pacific Ocean on 20 July 1913.

## 4. Early Comments on the Spectrum of Detached Subauroral Arcs Interpreted as STEVE Arcs

Størmer does not mention any color impression for naked-eye observations, likely because of the weak luminosity of the observed arcs. This is typical for naked-eye observations of STEVE arcs today. Not mentioned in his main work on “feeble homogeneous arcs of great altitude” from 1935 but in two others from 1911 and 1912 published in Dutch (Størmer, 1911) and French (Størmer, 1912), Størmer's team used two different types of photo plates to measure the height of the isolated high altitude arc observed on 22 February 1911. According to Størmer, both types of plates are only sensitive in the blue and near-UV spectral range. He explains that he was surprised that the arc was barely visible on the plates after an exposure time of up to 20 s, and most exposures failed. At his Bossekop auroral station, he needed only 2 to 5 s for comparable bright arcs. That means that this arc must have been significantly fainter in the blue and near-UV spectral range than homogeneous aurora arcs within the auroral oval exhibiting a comparable luminosity in naked-eye observations. His first interpretation was that the arc's spectrum must consists only of the bright green-yellow aurora line (Størmer, 1912). In a further work written in German (Størmer, 1931) and published after his second observation of an arc of the same type on 29 September 1930 he presents further detailed descriptions. He concludes that his first interpretation was incorrect because he did not see any signs of the 5,577 Å aurora line using an extremely powerful pocket spectroscope.

Størmer reports more details for this second observation in his work from 1935: “ … The arc remained across the heaven for about half an hour without sensible change. It was feebly luminous and without rays. Looking at it through a pocket-spectroscope of Lord Rayleigh's construction (at $20^h\ 12^m$) I could not discover any lines; even the green aurora line was not visible … ” Later that night, Størmer observed a feeble aurora glow near the northern horizon with the same spectroscope. He notes: “… only a feeble glow near the horizon; in the pocket-spectroscope directed toward this glow, the aurora line was visible till about $2^h\ 30^m$ …”

Størmer published only one spectrum (Størmer, 1939, 1942) for “feeble homogeneous arcs of great altitude” recorded on 5 March 1938. In his paper from 1942, Størmer mentions that “… It is remarkable how strong the oxygen line 6300 Å is as compared with the green line 5577 Å. The positive nitrogen bands near 6550 Å are about the same intensity as the line 5577 Å …” Because Størmer did not publish background spectra, it is difficult to interpret his spectrum quantitatively. It is possible that the emission of a faint, visually not visible “picket fence” contributed to the weak green line and N1 first positive (1P) emissions. Mende et al. (2019) report that the N1 first positive luminosity of an observed “picket fence” was 39% of the green line luminosity.

Størmer does not mention continuous spectra for any of his observations. However, the absence of spectral lines as found for his observation on 29 September 1930, significantly weaker luminosity in the blue and near-UV spectral range compared to homogeneous arcs in the auroral oval as found for his observation on 22 February 1911, is consistent with a broadband emission in the visual spectral range.

We have found that descriptions of continuous spectra for comparable isolated arcs, interpreted as STEVE arcs, exist in very rare reports, decades older than Størmer's. Bond et al. (1889) present four such descriptions in a report that summarizes aurora observations at the Harvard College Observatory or nearby sites for the period 1840–1888. The report for 24 August 1869 states, “August 24. Aurora; also a narrow band of light in a great circle from horizon to horizon nearly. This showed a continuous bright spectrum with telescope and with chemical spectroscope … At $20^h\ 25^m$ [$10^h\ 13^m$ P.M.] … the band was on a circle of declination all the way … The band was sinuous. It was roughly estimated as 2.5° wide and as moving southward … at the rate of 3° a minute … Bars crossed this band or formed another south of it, obliquely pointing toward the zenith. They moved slowly from east to west, continuing to point to the zenith.” Bond et al. (1889) report on continuous spectra associated with detached arcs in three other cases, observed on 29 June 1869, 3 September 1869, and 12 September 1881. The phenomenological descriptions for these detached subauroral arcs are in good agreement with modern descriptions of STEVE arcs.

It is known from amateur observations that “picket fence” structures show slow drifts from east to west. A possible explanation for the reported bars that form another band south of the band is a “picket fence” composed of multiple ray-like substructures. Also, discrete substructures in STEVE arcs are documented with a distinct east to west drift in naked-eye or camera-documented observations in case of sub-1 s exposure times (Hunnekuhl et al., 2019). Discrete E-W drifting substructures in STEVE arcs are a possible interpretation of the reported bars that crossed the band.

## 5. Conclusions

Størmer's work presents phenomenological descriptions for "feeble homogeneous arcs of great altitude" that are compliant with modern descriptions of naked-eye and camera-documented observations of STEVE arcs. The knowledge in the pre-space era neither allowed a comprehensive understanding of their specific characteristics nor the identification of a connection with SAIDs. Størmer was aware that these structures have distinct characteristics and occur in the form of isolated arcs detached from the main auroral activity. However, his descriptions do not give rise to the assumption that he interpreted these structures as atypical for aurora. He classified them as a rare type of aurora. We interpret Størmer's altitude measurement results as the first ones for STEVE arcs presented in the literature based on coordinated simultaneous multistation measurements. They are in good agreement with results published by Archer, St.- Maurice, et al. (2019). Størmer's descriptions benefit much from early amateur observer descriptions, partly presented in his publications.

As an example, Størmer's work shows that historical knowledge about STEVE structures exists relevant to modern discussions on this phenomenon. Descriptions of comparable isolated arcs in a work of Bond et al. (1889), reported with continuous spectra, are further important examples.

Størmer asked and searched for amateur data to include it in his work. Amateur observer and citizen science data are still of great importance for ongoing research across the space weather field. These data initiated the modern research on the STEVE phenomenon in the post-IGY era and will certainly bring new important impulses to increase our knowledge on it. More efforts to encourage amateur observers and citizen scientists worldwide to contribute to the ongoing space weather research is highly desirable.

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