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RESEARCH ARTICLE OPEN ACCESS

Fan-shaped aurora as seen from Japan during a great magnetic storm on February 11, 1958

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Abstract – During a great magnetic storm on Feb 11, 1958, a fan-shaped aurora was photographed at Memambetsu, Hokkaido, Japan – the first and oldest photograph record of auroras observed in Japan, accompanied by many hand-made drawings, thus, portraying a rare opportunity of coexistence between photograph images and hand-made drawings. In fact, the same portrayal reminds us of the great red aurora with fan-shaped white pillars observed during the 1872 and 1770 great magnetic storms. The hand-made sketches, photographs, and the spectral data revealed that the white pillars and red glow of the fan-shaped aurora were dominated by auroral green and red lines, respectively. From the analysis of newly digitized microfilm data and hand-made drawings, we found that the fan-shaped aurora appeared during the peak activity of magnetic storm and moved westward at 0.4 km/s at 400-km altitude at 38°–40° magnetic latitudes, which is consistent with the enhanced convection pattern in the middle latitude at storm time. Such a fan-shaped aurora can fundamentally characterize the middle-latitude evening-to-midnight auroras during great magnetic storms, which show the most destabilized transient appearance of the inner magnetosphere.

Keywords: low-latitude aurora / magnetic storms / microfilm data / hand-written drawings

1 Introduction

Red auroras occasionally appear even in middle-latitude countries such as Japan and China during great magnetic storms (Nakazawa et al., 2004; Kataoka et al., 2017). These phenomena are rare, but potentially harmful occurrences that disrupt man-made ground-based systems including power grids (Lanzerotti, 1979, 1983; Baker & Lanzerotti, 2016; Kataoka & Ngwira, 2016). Therefore, understanding such auroras may help mitigate the possible natural hazard they bring. Recent studies revealed that an impressive fan-shaped aurora, characterized by a red glow and white pillars, appeared over Kyoto during the historically greatest magnetic storm on September 17, 1770 (Kataoka & Iwahashi, 2017). The magnetospheric and ionospheric current system to create the bright white pillars of the September 1770 event infers the possible existence of large geomagnetically induced currents even in middle latitudes during great magnetic storms.

In the modern-day era, one of the strongest solar activities occurred in 1957 around the solar maximum of the solar cycle 19 when the monthly averaged sunspot number exceeded 350, according to Sunspot Number Version 2.0 available at WDC-SILSO. In fact, auroras appeared over Japan several times in a few years around the solar maximum, as recorded in Japanese newspapers on August 9, 1956, September 5, 1956, March 2, 1957, May 27, 1957, September 13, 1957, February 11, 1958, and March 6, 1958. Two events on September 1957 and February 1958 occupy the top-five greatest magnetic storms recorded by the final Dst index since 1957 available at WDC for Geomagnetism, Kyoto.

Particularly, on February 11, 1958, several Japanese meteorologists observed red auroras from northern Japan by hand-made drawings and photographs for the first time. Among the drawings, we found a sketch of a fan-shaped aurora from Memambetsu Magnetic Observatory (43 55° N, 144 12° E, 34° magnetic latitude) similarly depicted the appearance of the September 1770 event. In this paper, the microfilm data of the photographs are digitized to revisit the unique event. Moreover, the time variation of fan-shaped aurora and the spectra are analyzed in detail, to give further insights into the possible mechanisms causing the fan-shaped aurora during great storms.

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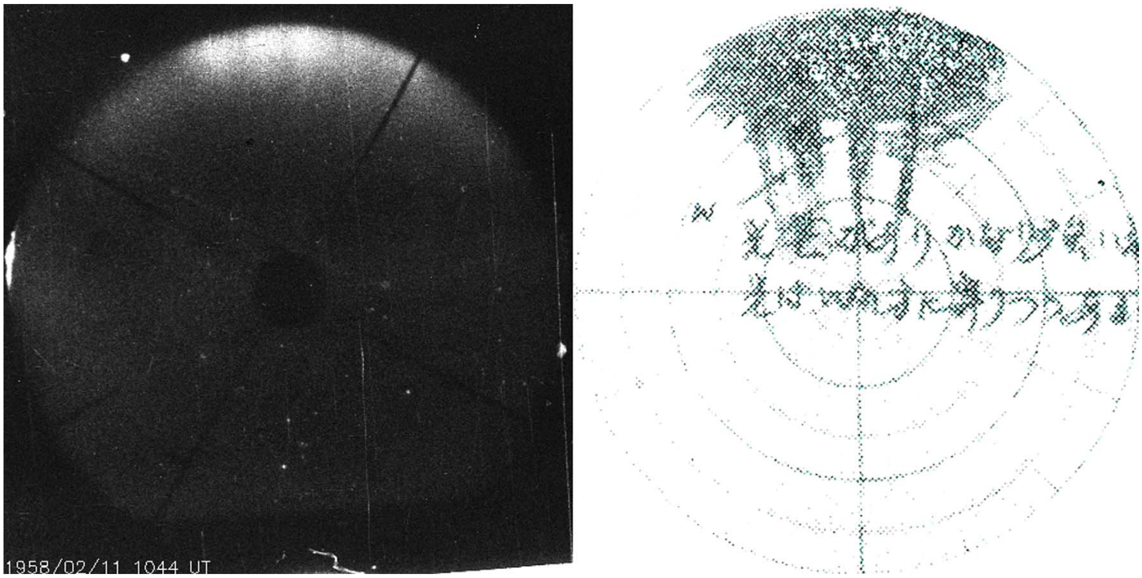

Fig. 1. Sample photograph (left, at 1044 UT) and hand-made sketch (right, at 1037 UT) of the auroras, as observed at Memambetsu Magnetic Observatory on February 11, 1958. Both images are in the all-sky format, where zenith is the center and geographic north is to the top.

2 Data

The microfilm data provided by Kakioka Magnetic Observatory was accompanied by an official report (Kakioka Report, 1967), which cites: "*This (the camera system) was furnished with a 30-cm convex mirror, a 16-cm plane mirror, and a camera lens whose focal ratio is 0.95.*" The exposure time for this event was 7 s. The microfilm data used in this study had 1-min time cadence, which was enlarged from the original 16-mm SAKURA SSS film as developed by PANDOL for 15 min at 20 °C.

We digitized the microfilm data of all-sky photographs taken at Memambetsu Magnetic Observatory, using a microfilm scanner ScanPro 2000 at the Data Center for Aurora in the National Institute of Polar Research, under a fixed exposure setting and a fixed resolution of 600 dpi. After digitization, we manually centered, scaled, and rotated the images without altering the contrast or brightness. The final data were saved in an all-sky format, where zenith is the center, geographic north is to the top, and the 90° from the zenith is at the edge of the square, as shown by the image samples in Figure 1, which were displayed at different times with the pillar-like structure appearing in both photograph and sketch. Figure 2 shows coordinate transformed image and sketch, showing clearly the actual appearance of the fan-shaped auroras. Note that the number and separations of pillar-like structures are similar between photograph and sketch.

3 Results

3.1 Temporal evolution and the spectra

Here, we first point out that the fan-shaped aurora appeared during the peak time of magnetic storm when the final Dst index was −426 nT at 1000–1100 UT on February 11, 1958. The spectrograph was operated in four time-intervals, starting from 0955 to 1030 UT, 1030 to 1130 UT, 1130 to 1230 UT, and 1230 to 1330 UT. Figure 3 shows the measured intensity of red (630.0 nm), green (557.7 nm), and blue (427.8 nm) lines for elevation angles of 0°, 30°, and 60°. The original data is from Kakioka Report (1967) which includes a table showing the intensity values of a red line (630.0 nm), the doublet (636.4 nm), a green line (557.7 nm), and Nitrogen bands (427.8 nm, 391.4 nm, and 388.4 nm) for elevation angles of 0°, 30°, 60°, 75°, 80°. Another display of the same multi-wavelength data was also briefly introduced by Saito et al. (1994).

Notably, the structure of the so-called white pillars could not be apparently seen in the microfilm data, while the corresponding patches could be seen, possibly because human-eye sensitivity is peaked at green colors but weak in red colors. As shown in Figure 3, the red line was dominant in the auroras, as well as in the photographs, for more than three hours, approximately 100 times larger than the green line. However, the appearance of greenish colors could be comparable for human eyes.

In terms of white pillars, the official report of photographs (Kakioka Report, 1967) noted that "*the maximum brightness of the aurora occurred during 1030–1050 UT. Several columns of ray structure were observed at the time of maximum brightness. The color of the glow was dark red, while the columns were yellowish at the lower part and rather white at the upper part.*" Here, it is also important to note that the yellowish color is typically known for the near-horizon appearance of standard green-line auroras. In fact, in Figure 3, the green line is intense enough to be visible (>1 kR) by human eyes. Therefore, from the spectral data, it is interpreted that white pillars are dominated by green line, with a small contribution from blue line.

Nevertheless, another observer explained (written in Japanese) the hand-made drawings at Memambetsu as documented in Japan Meteorological Agency (1958a), that those pillars were already watched past approximately an hour prior to the peak auroral activity as:

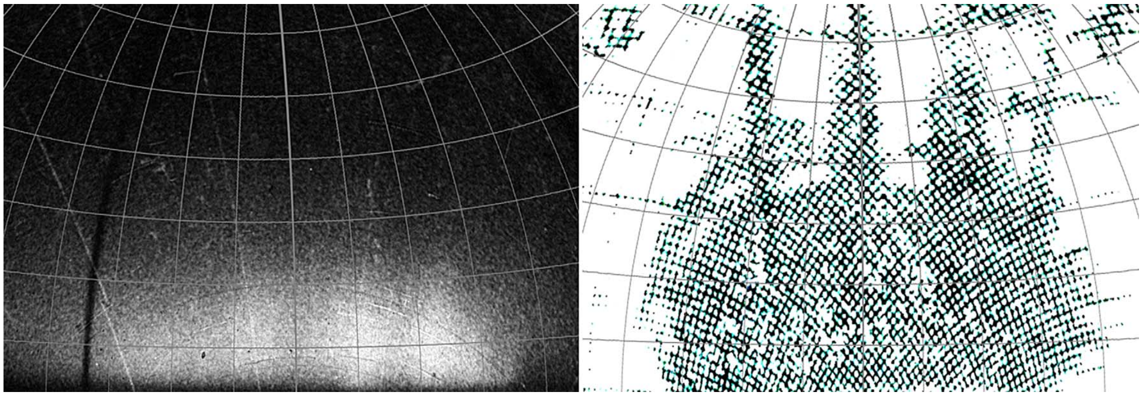

Fig. 2. Coordinate transformed photograph (top, 1044 UT) and hand-made sketch (bottom, 1037 UT) of the auroras, as observed from Memambetsu Magnetic Observatory on February 11, 1958, at a view looking toward the geographic north. Elevation angle and azimuth angle grids are shown every 10°.

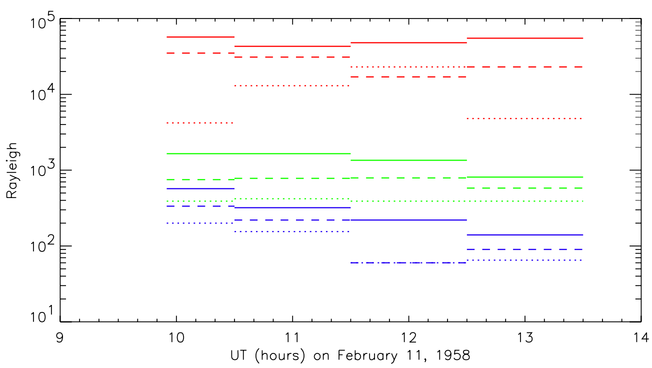

Fig. 3. Intensity variation of 630.0 nm (red), 557.7 nm (green), and 427.8 nm (blue) at different elevation angles of 0° (solid lines), 30° (dashed lines), and 60° (dotted lines). Significant visible emissions also exist even at the 60° elevation angle.

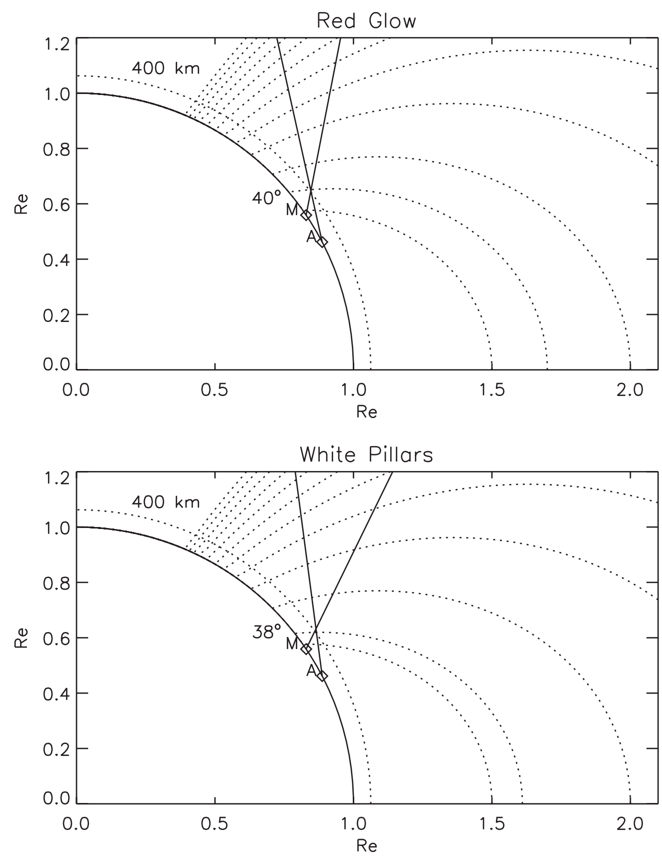

Fig. 4. Observation geometry of (top) red glow and (bottom) white pillars in the geomagnetic coordinate by Memambetsu Magnetic Observatory (*M*, 34° magnetic latitude) and Aikawa Weather Station (*A*, 27.5° magnetic latitude). The top panel shows the top part of red glow with 45° elevation angle at *M* and with 15° elevation angle at *A*. The bottom panel shows the top part of white pillars with 60° elevation angle at *M* and with 20° elevation angle at *A*.

> "It was like a mountain fire far away. After 0930, pillars appeared alongside with the density change. Around 1000 UT, the color of the pillar was white, and it was like a searchlight from the ground; four pillars were recognized. After 1045 UT, the arc without pillars began to decay. After 1100 UT, the color was faint red, and the 1–2 min or 2–3 min luminosity oscillation was observed. The elevation angle was approximately 45°, while the strong pillars were likely up to 60°."

Here, the luminosity oscillation in the quasi-periodic Pc4 range (Saito, 1969) after 1100 UT was an interesting note, as it could be related to the strong geomagnetic pulsation activities associated with the responsible mechanisms causing red auroras.

3.2 Geometrical analysis

The white pillars should be located equatorward of the red glow to reproduce the taller appearance of the former than of the latter, as the emission height of green curtains should typically be lower than the red arcs (Shiokawa et al., 1997). Figure 4 illustrates the restriction that can be made for the possible emission altitude, using another sketch from Aikawa Weather Station (27.5° magnetic latitude), where the auroras appeared

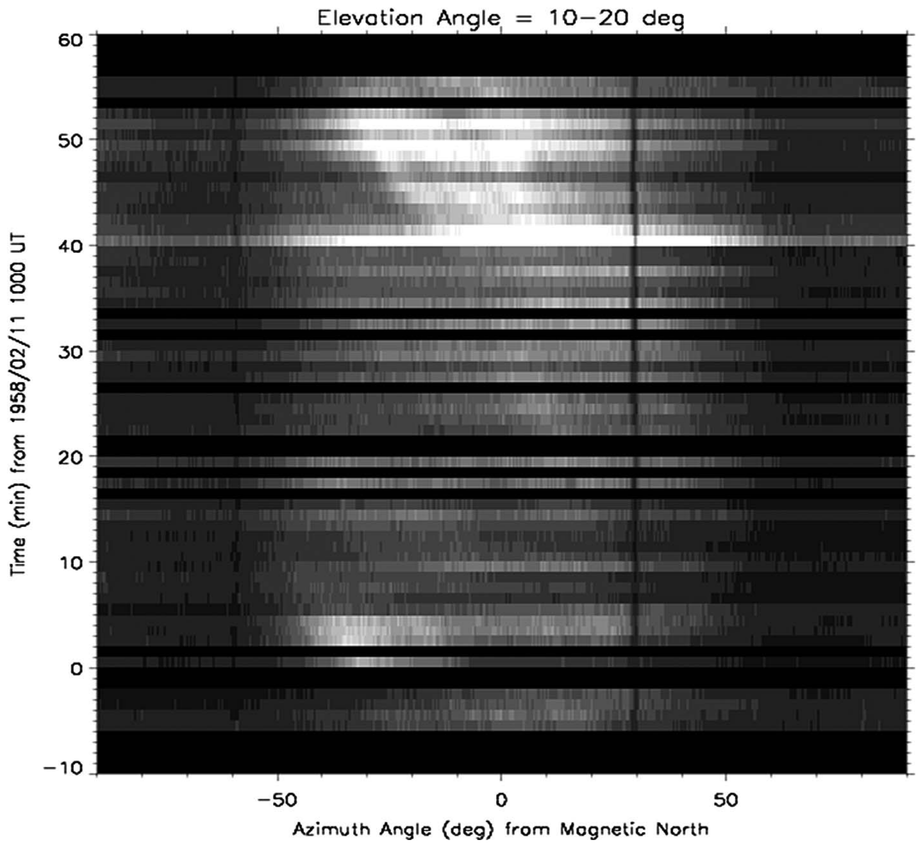

Fig. 5. Time–position diagram of panchromatic auroral intensity at 0950–1100 UT at 10–20° elevation angle. Time is to the top, and the horizontal axis is the azimuth angle from the magnetic north.

15–20° elevation angle to the north (Japan Meteorological Agency, 1958b). From a triangulation analysis, it is estimated that the red glow was at 40° magnetic latitude, while the white pillars were at 38° magnetic latitude. Maximum altitudes of both emissions were comparable at an altitude of approximately 400 km.

Figure 5 shows the time-position diagram, as obtained from the digitized microfilm data to measure the east-west motion of the auroras at an elevation angle of 10–20°. Several patches, possibly along with the white pillars (see Fig. 1), were apparent at 1040–1050 UT and moved westward at approximately 10° every five min on average, without significantly changing the separations of the patches. Combined with the possible geometry in Figure 4, The westward propagation speed was estimated at ~0.4 km/s at 400-km altitude.

4 Discussions

4.1 Pre-midnight, middle-latitude, and large-scale auroras

Here, we discuss the possibility that the fan-shaped aurora of the February 11, 1958 event, as highlighted in this study, is a fundamental characteristic of the middle-latitude evening-to-midnight sector auroras during great magnetic storms. Kataoka & Iwahashi (2017) recently suggested that the fan-shaped aurora of the September 1770 event was a huge aurora covering a significantly large portion of the northern sky and that it appeared at the evening-to-midnight sector. Moreover, the huge fan-shaped appearance was due to the geometrically looking-up location of a series of tall columns aligned with the inclined magnetic field of the middle latitude.

Another beautiful example is the fan-shaped aurora that appeared on March 1, 1872, as illustrated by E.L. Trouvelot (Fig. 6). The date is puzzling, as no magnetic storms were recorded at that time. Instead, a historically large magnetic storm was recorded on February 4, 1872 (Cliver & Svalgaard, 2004), accompanied by many auroral sightings globally (Silverman, 2008), which Willis et al. (2007) reported to extend for three days from February 4–6. Thus, the actual observation date of Trouvelot was presumed to be any evening in this range. In fact, Trouvelot (1882) accounted: "*In 1872 I, myself, observed an aurora which apparently continued for two or three consecutive days and nights*". The depicted stars are also consistent with the simulated star constellations as seen from the middle latitude cities at 9:25 p.m. on February 4–6. Furthermore, the depicted stars indicate that the fan-shaped aurora at that time was huge and covered a significant portion of the northern sky, where the big dipper reached the elevation angle of 50°. The large-scale appearance of the fan-shaped aurora is consistent with the estimation by Kataoka & Iwahashi (2017).

From the above discussions, we suggest that the fan-shaped aurora of the February 1958 event shows such a fundamental characteristic to historical magnetic storms, i.e., large-scale auroras covering a significant portion of the northern sky of

Fig. 6. An illustration entitled "Aurora Borealis as observed on March 1, 1872 at 9:25 p.m." by Etienne Leopold Trouvelot (The New York Public Library Digital Collections, https://digitalcollections.nypl.org/items/510d47dd-e6cd-a3d9-e040-e00a18064a99).

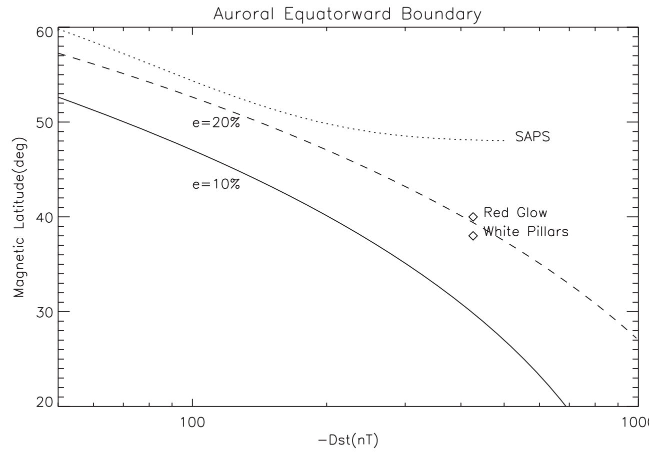

Fig. 7. Magnetic latitude of model equator boundaries of the red aurora (Kataoka & Iwahashi, 2017) and the sub-auroral polarization stream (Wang et al., 2008). Diamonds show the red glow and white pillars of February 11, 1958 event.

middle-latitude at evening-to-midnight sector. Moreover, careful reviews of recent great magnetic storms give notice of the fan-shaped appearance of middle-latitude auroras during large magnetic storms (e.g., Miyaoka et al., 1990).

4.2 Possible mechanisms of fan-shaped aurora

Here, we briefly discuss the possible mechanisms of fan-shaped auroras. We simply hypothesize that the red lines were a standard stable auroral red (SAR) arc, and that the other colors reflect "white pillars" due to field-aligned currents carried by precipitating electrons. In a similar recent example, Mendillo et al. (2016) demonstrated a detailed analysis of the SAR arc, where several superimposed patches of green line emission were found during a magnetic storm. Enhancements in total electron content and radio wave scintillations at the patches support electron precipitation from the plasma sheet (Aarons, 1987). The longitudinal separation of the patches was 3–4°, reflecting some fundamental spatial scales for modulations of plasma sheet population, where the patches moved equatorward from 60° to 56.6° magnetic latitude during a 40 min period.

To explain the SAR arcs, Cole (1965) proposed a thermal conduction model by Coulomb collision between electrons and ring current ions, which was extended by Kozyra et al. (1997). Hasegawa & Mima (1978) suggested that kinetic Alfven waves produce direct precipitation of the heated electrons, which can be consistent with the observed luminosity oscillations in the February 1958 event. Hence, these standard theories may explain some of the relatively homogenous red emissions, but may not be able to explain the structural fan-shaped white pillars.

An interchange-ballooning instability between the energetic ring current ions and less energetic plasma sheet particles is expected to occur in the inner magnetosphere during the magnetic storms (Sazykin et al., 2002; Ebihara et al., 2005) to cause undulations near the equatorward edge of the diffuse aurora. Pressure gradients in the ring current drive field-aligned currents in and out of the ionosphere (Vasyliunas, 1970) that causes the azimuthally repeating pairs of a field-aligned current pattern associated with the interchange pattern to create the white pillars. Furthermore, the plasma mixing associated with the interchange-ballooning instability can cause a standard SAR-arc type electron heating that appears as the red aurora behind the white pillars.

Therefore, the new finding of the westward motion of the fan-shaped aurora can be interpreted as the bulk motion of the interchange pattern. For example, the equatorial azimuthal speed of the plasmasphere undulations is in the order of 1 km/s at the ionosphere (Goldstein et al., 2004). Related phenomena include auroral undulation (Lui et al., 1982; Mendillo et al., 1989; Nishitani et al., 1994), sub-auroral polarization stream (Foster et al., 1994; Horvath & Lovell, 2015), and plasmasphere ripples (Goldstein et al., 2005).

Figure 7 shows the model of the equatorward edge of auroral oval against the Dst index, as suggested by Kataoka & Iwahashi (2017), as well as the model of sub-auroral polarization stream (Wang et al., 2008). The aurora of the February 1958 event is located in-between the theoretical curves of the sub-auroral polarization stream and the equatorward boundary of auroral oval. Thus, the fan-shaped aurora would provide an important hint for understanding the complex interplay among the plasmasphere, ring current, and plasma sheet in the magnetosphere, as well as the ionospheric trough, sub-auroral polarization stream and Region-2 field-aligned current system in the ionosphere (e.g., Kataoka et al., 2007). Therefore, the coexistence of several different sub-auroral phenomena would be an important topic for future investigations, and further suggests the predictability of the fan-shaped aurora by inner magnetosphere simulation, coupled with the ionosphere. On this regard, globally distributed old data, combined with recent space-age knowledge, will also prove useful in shedding new lights to the complexities of rare great magnetic storms.

5 Conclusions

We revisited a great magnetic storm event that occurred on February 11, 1958, via an investigation of the unique data set of the fan-shaped aurora appeared during the peak activity of the magnetic storm. The hand-made sketches, photographs, and the spectral data revealed that the white pillars and red glow of the fan-shaped aurora were dominated by auroral green and red lines, and the magnetic latitudes were estimated to be 38° and 40°, respectively. It was also estimated that the white pillars moved westward at 0.4 km/s, which is consistent with the enhanced convection pattern at evening-to-midnight sector in the middle latitude.

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