Bhaskar Ankush, T. (Orcid ID: 0000-0003-4281-1744)

Hayakawa Hisashi (Orcid ID: 0000-0001-5370-3365)

Oliveira Denny, M. (Orcid ID: 0000-0003-2078-7229)

Blake Sean, Patrick (Orcid ID: 0000-0001-9042-3557)

Ebihara Yusuke (Orcid ID: 0000-0002-2293-1557)

An analysis of the Trouvelot's Auroral Drawing on 1/2 March 1872: Plausible Evidence for Recurrent Geomagnetic Storms

Ankush Bhaskar* (1-2), Hisashi Hayakawa** (3-6), Denny M. Oliveira (1, 7), Sean Blake (1-2), Sam M. Silverman (8), and Yusuke Ebihara (9-10).

(1) NASA Goddard Space Flight Center, Greenbelt, MD, United States

(2) Catholic University of America, Washington DC, United States

(3) UK Solar System Data Centre, Space Physics and Operations Division, RAL Space, Science and Technology Facilities Council, Rutherford Appleton Laboratory, Harwell Oxford, Didcot, Oxfordshire, OX11 0QX, UK

(4) Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, 4648601, Japan

(5) Institute for Advanced Researches, Nagoya University, Nagoya, 4648601, Japan

(6) Nishina Centre, Riken, Wako, 3510198, Japan.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2020JA028227

(7) Goddard Planetary Heliophysics Institute, University of Maryland, Baltimore County, Baltimore, MD, United States

(8) 18 Ingleside Road, Lexington, MA 02420, USA

(9) Research Institute for Sustainable Humanosphere, Kyoto University, Uji, 6110011, Japan

(10) Unit of Synergetic Studies for Space, Kyoto University, Kyoto, 6068306, Japan

* a.bhaskar@nasa.gov; ankushbhaskar@gmail.com

** hisashi@nagoya-u.jp; hisashi.hayakawa@stfc.ac.uk

Abstract

This work examines Trouvelot's observations and drawing of an auroral display during the night of 1 March 1872. It is known that the auroral oval moves equatorward to mid- and even low-latitudes during large geomagnetic storms. Trouvelot's graphical record of the great aurora on 1 March 1872 has been often cited as a remarkable example of a mid-latitude aurora, although it is puzzling that this occurred on a geomagnetically quiet day. Kataoka *et al*. (2019, *JSWSC*, **9**, A16) even regarded this as a dating error. Here, we investigate Trouvelot's descriptions and available geomagnetic measurements in detail. Our analysis shows that the original date of Trouvelot's auroral drawing is most probably accurate. Moreover, Trouvelot's descriptions and the observational site show that the auroral visibility fell at the beginning of 2 March 1872 in Greenwich Mean Time (GMT). Consulting simultaneous variations of magnetograms at Helsinki and Greenwich, we found that the nightside aurora specifically coincides with the initial phase of the storm (substorm) and suggests a close association with a substorm triggered by sudden magnetospheric compression. This case study shows that even short geomagnetic storms can be overlooked in

a daily Aa index and they can also cause mid-latitude aurorae. Moreover, we found ≈ 27-day intervals between this storm, the extreme storms on 4-6 February 1872, and another "bright aurora" that was reported on 6 January 1872. Based on their interval, these mid-latitude aurorae have probably resulted from recurrent solar activity.

1. Introduction

It is generally understood that mid-latitude aurorae appear with great magnetic storms (*e.g.*, Vallance Jones, 1992; Daglis *et al*., 1999; Schlegel and Schlegel, 2011; Cid *et al*., 2014, 2015; Saiz *et al*., 2016), resulted from interplanetary coronal mass ejections (ICMEs) or shock with corotating interaction region, with the southward interplanetary magnetic field (Gonzalez *et al*., 1994; Borovsky & Denton, 2006; Richardson *et al*., 2006). This was especially the case with the extreme storms such as the Hydro-Québec storm in March 1989, where significant ICMEs cause one of the most extreme geomagnetic storms in the space age and significant extension of the auroral oval (Allen *et al*., 1989; Yokoyama *et al*., 1998; Cid *et al*., 2014; Boteler, 2019). As such, mid-latitude auroral reports have formed one of the important clues to understanding the space weather and space climate in the past (*e.g.*, Silverman, 1992; Vaquero *et al*., 2010; Lockwood & Barnard, 2015; Lockwood *et al*., 2016; Vázquez *et al*., 2016; Domínguez-Castro *et al*., 2016; Riley *et al*., 2018; Hayakawa *et al*., 2019c).

Statistical studies show a fairly good empirical correlation between the storm intensity (minimum Dst index) and the equatorward boundary of the auroral oval (Schulz, 1997; Yokoyama *et al*., 1998; Silverman, 2006). Indeed all four outstanding aurorae reviewed by Chapman (1957) – namely those in September 1859 (Tsurutani *et al*., 2003; Siscoe *et al*., 2006; Silverman, 2006; Gonzalez *et al*., 2011; Cliver & Dietrich, 2013; Hayakawa *et al*., 2018c; Lakhina & Tsurutani, 2018; Blake *et al*., 2020), February 1872 (Tsurutani *et al*., 2005; Silverman, 2008; Hayakawa *et al*., 2018a), September 1909 (Silverman, 1995; Hayakawa *et al*., 2019a; Love *et al*., 2019a), and May 1921 (Silverman & Cliver, 2001; Hapgood, 2019) – have been confirmed as geomagnetic superstorms of Dst/Dst* ≤ −500 nT (Cliver & Dietrich, 2013; Riley *et al*., 2018; Hayakawa *et al*., 2018a, 2019b; Love *et al*., 2019a, 2019b) and compared with two more superstorms with mid-latitude aurorae in October/November 1903 and March 1946 (Hayakawa *et al*., 2020a, 2020b).

Nevertheless, there seems to be some reported mid- to low-latitude aurorae during periods of quiet to moderate geomagnetic activity. Silverman (2003) reviewed these aurorae and named them "sporadic aurorae" (Silverman, 2003), setting its threshold in daily *aa* index as ≤ 55 (Silverman, 2003). They are generally faint aurorae, while their physical properties such as duration and relationship with substorms are currently under further investigations (Silverman, 2003; *c.f.*, *e.g.*, Akasofu, 1964; Hayakawa *et al*., 2018b). Although their physical mechanism has not been fully understood, follow-up works have recovered such sporadic aurorae in other mid- to low-latitude regions (Willis *et al*., 2007; Vaquero *et al*., 2007, 2013; Hayakawa *et al*., 2018b; Oliveira *et al*., 2020). Therefore, it would be intriguing to collect more parallel data, critically reconsider auroral reports during quiet to moderate geomagnetic activity, and consider their reliability and background physics in comparison with geomagnetic measurements at that time.

Étienne L. Trouvelot's famous auroral drawing on 1 March 1872 (Figure 1; Trouvelot, 1882; see also Odenwald, 2015) is one such puzzling case (see *e.g.*, Kataoka *et al*., 2019), given that the aurora was reported in mid-latitudes despite quiet to moderate geomagnetic activity (daily *aa* = 13). Indeed, Kataoka *et al*. (2019) have recently revisited this auroral drawing and criticized Trouvelot's original dating on 1 March 1872, "as no magnetic storm was recorded at that time". Kataoka *et al*. (2019) instead claimed that Trouvelot's drawing was misdated and associated it with the great magnetic storms on 1872 February 4 – 6 when aurorae were seen in the low-latitude area (*c.f.*, Willis *et al*., 2007; Silverman, 2008; Hayakawa *et al*., 2018a), based on their criticism. Therefore, it would be of significant interest to consider if Trouvelot's drawing was correctly dated (Trouvelot, 1882; Odenwald, 2015) or misdated from the February storms (Kataoka *et al*., 2019). If the dating is correct, this auroral drawing belongs to a sporadic aurora (*e.g.*, Silverman, 2003) and questions us its cause. In order to address this scientific question, we examine geomagnetic activities and the possible solar wind drivers based on contemporary observations.

In this study, we, therefore examine Trouvelot's original drawing and description to evaluate the reliability of Trouvelot's own dating for this auroral drawing, compare them with contemporary auroral records, contextualize the temporal and spatial evolution of this aurora with available magnetic measurements, and consider the case and cause of sporadic aurorae.

Figure 1: Trouvelot's auroral drawing at 21:25 LT on 1872 March 1 (Trouvelot, 1882), with courtesy of the Rare Book Division, The New York Public Library, The New York Public Library Digital Collections. (http://digitalcollections.nypl.org/items/510d47dd-e6cd-a3d9-e040-e00a18064a99)

2. Trouvelot's Auroral Observations

Étienne Léopold Trouvelot (1827 – 1895) was a French artist and astronomer, who emigrated from France to the United States in 1852 and worked in New England afterward. He started working on astronomy after a series of auroral spectacles in 1870 (*e.g.*, Hale, 1895). He is well known for his astronomical drawings (Trouvelot, 1882), which are currently preserved in the New York Public Library. Among them, Trouvelot published an auroral drawing dated on 1 March 1872 (Figure 1) as “Plate IV” in his monograph with his own description in his appendix (Trouvelot, 1882, p. 161):

PLATE IV. AURORA BOREALIS.

As observed March 1, 1872, at 9h. 25m. P. M. The view presents the rare spectacle of an aurora spanning the sky from east to west in concentric arches [28*c*]. The Polar Star is nearly central in the back-ground, the constellation of the Great Bear on the right and Cassiopeia's chair on the left. The large star at some distance above the horizon on the right is Arcturus. The almost black inner segment [28*b*] of the aurora resting upon the horizon, has its summit in the magnetic meridian [32*a*], which was in this case a little west of north, its arc being indented by the bases of the ascending streamers [28*c*]. Both streamers and arches were, when observed, tremulous with upward pulsations [29*b*] and there was also a wave-like movement of the streamers from west to east [29*a*]. The prevailing color of this aurora is a pale whitish green [28*c*] and the complementary red appears especially at the west end of the auroral arch. The summits of the streamers are from four hundred to five hundred miles above the earth [31*a*] and the aurora is therefore a phenomenon of the terrestrial atmosphere [32*b*] rather than of astronomical observation proper.

According to Trouvelot’s description, the aurora arch extended along the dark segment having its center at the magnetic meridian, the aurorae moved upward and eastward, the aurora was mostly pale whitish-green, whereas the west end of the auroral arch had a reddish color. This means the aurora was bright enough for its rays and pulsations to be detected with the unaided eye, and both its greenish emission (wavelength (WL) = 555.7 nm) and reddish emission (WL = 630.0 nm) coexisted in it as a background. Interestingly, Trouvelot (1882, p.

28) himself reported the auroral color in general as: “For the most part the auroral light is either whitish or of a pale, greenish tint; but in some cases, it exhibits the most beautiful colors, among which the red and green predominate”. Therefore, it is expected that faint greenish emissions (WL = 557.7 nm) were detected as whitish in color (see *e.g.*, Hayakawa *et al.*, 2017; Carrasco *et al.*, 2017; Ebihara *et al.*, 2017; Stephenson *et al.*, 2019). The whitish rays in the drawing (Figure 1) may indicate that its mixture with reddish emissions (WL = 630.0 nm) with weak brightness may have been detected as whitish in color as well, potentially with some contributions from bluish emissions (WL = 427.8 nm, N_{2+}).

As auroral phenomena were the origin of his astronomical interests, Trouvelot had watched aurorae and had spared an independent section for the auroral borealis in his monograph. In 1872, he observed “a brilliant aurora for over one hour” on January 6 and “an aurora which apparently continued for two or three consecutive days and nights” (Trouvelot, 1882, p. 30 and p. 36) as well. Trouvelot’s auroral reports have been occasionally cited in scientific journals as well. One of the good examples is his auroral report on 4 February 1872 (Figure 2), cited in Twining (1872, p. 276).

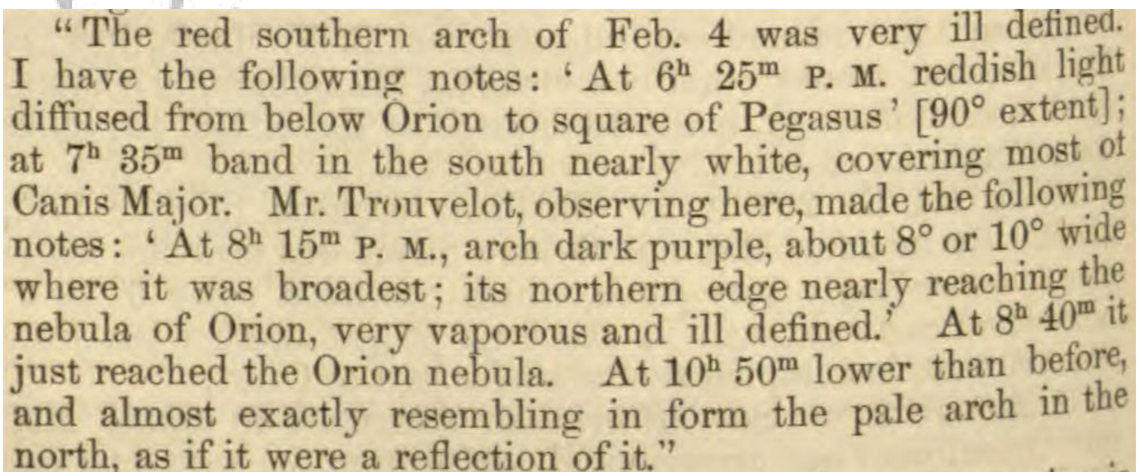

“The red southern arch of Feb. 4 was very ill defined. I have the following notes: ‘At 6^h 25^m P. M. reddish light diffused from below Orion to square of Pegasus’ [90° extent]; at 7^h 35^m band in the south nearly white, covering most of Canis Major. Mr. Trouvelot, observing here, made the following notes: ‘At 8^h 15^m P. M., arch dark purple, about 8° or 10° wide where it was broadest; its northern edge nearly reaching the nebula of Orion, very vaporous and ill defined.’ At 8^h 40^m it just reached the Orion nebula. At 10^h 50^m lower than before, and almost exactly resembling in form the pale arch in the north, as if it were a reflection of it.”

Figure 2: Trouvelot's auroral report on 1872 February 4, reproduced from Twining (1872).

On this basis, we consider Trouvelot had already started his astronomical observations around the Harvard College Observatory (N42°23′, W071°08′) at latest on 4 February 1872. This assumption is consistent with his documented connection with the Harvard College Observatory in the front cover of Trouvelot (1882) and in Hale's short biography (Hale, 1895). This assumption allows us to estimate the magnetic latitude of Trouvelot's observational site as 53.8° on the basis of the dipole assumption of the GUFM1 model (Jackson *et al*., 2000).

3. A Dating Error or a Sporadic Aurora?

On the other hand, Trouvelot's auroral drawing has recently had its date criticized and alternatively associated with the extreme storms on 4-6 February, "as no magnetic storms were recorded at that time" (Kataoka *et al*., 2019). Given its daily *aa* index = 13.2, the geomagnetic activity on 1 March 1872 is certainly considered as quiet to moderate, on the basis of Silverman (2003)'s threshold (daily $aa \leq 55$) as shown in the top panel of Figure 3.

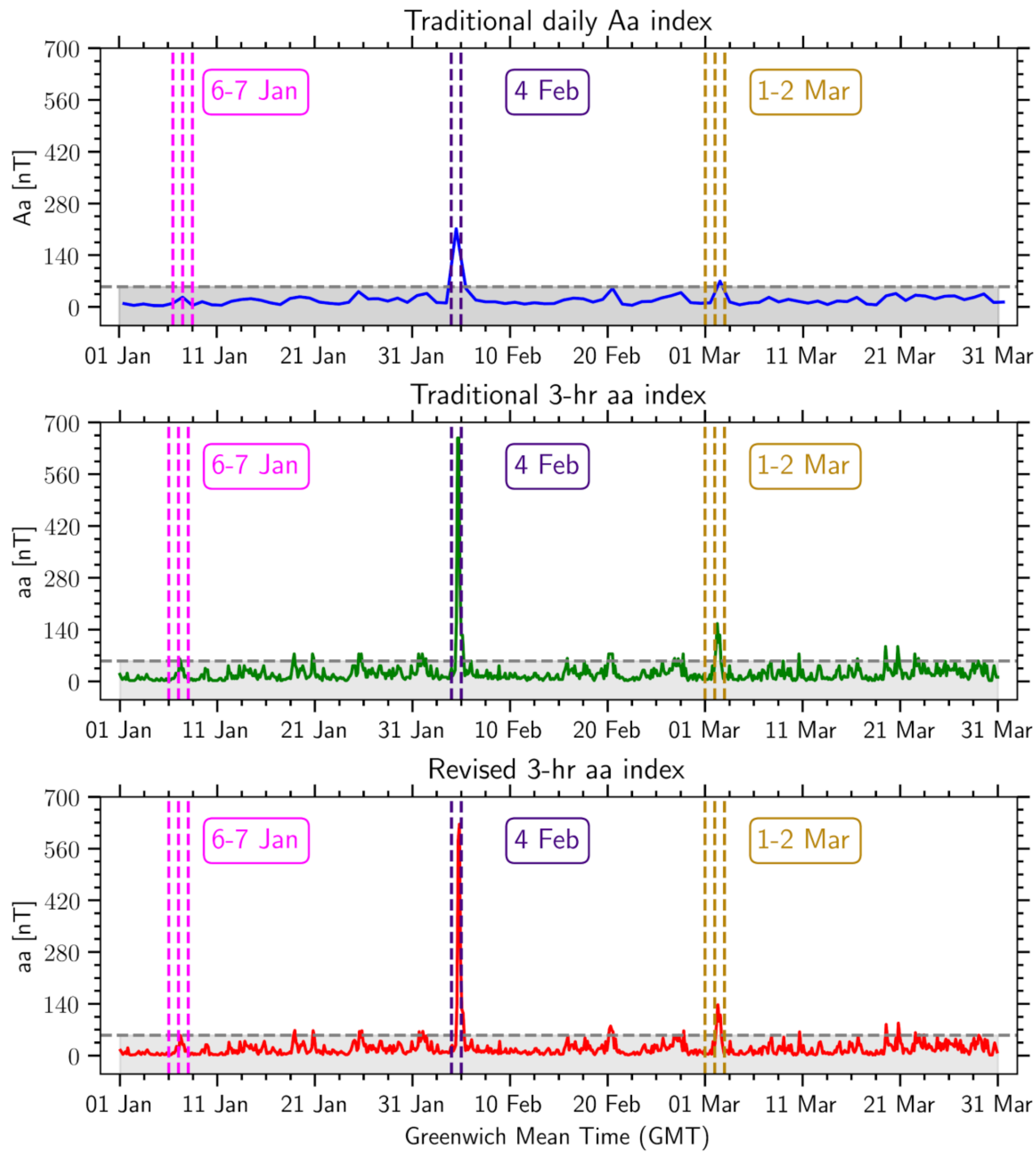


Figure 3: Aa index (Mayaud, 1972) and revised Aa index (Lockwood et al., 2018) from 1872 January to March, with a threshold (highlighted grey areas) of Aa = 55 suggested by Silverman (2003) and dates with candidate aurorae on 6 January, 4-6 February, and 1-2 March 1872.

However, caveats must be noted here, as the *aa* index was not specifically designed for high-latitude ionospheric variations. Nevertheless, Trouvelot's aurora was reported in 1872, far before the introduction of the AE index or SME index (Davis & Sugiura, 1966; Newell & Gjerloev, 2011). As such, auroral activity in the auroral zone may not be reflected in the *aa* index. Moreover, the *aa* index is with daily to tri-hourly resolution (Mayaud, 1972; Lockwood *et al*., 2018a, 2018b) and high-resolution magnetic measurements are needed to analyze the details of the geomagnetic activity back in that time, especially to deal with the small geomagnetic disturbances caused by Corotating Interaction Region (CIR) (Smith and Wolfe, 1976).

Moreover, Trouvelot's auroral report on 4 February 1872 (Figure 2) seems significantly different from his drawing dated on 1 March (Figure 1). On 4 February 1872, Trouvelot observed aurora at least from 20:15 LT to 22:50 LT, including 21:25 LT. Unlike Trouvelot's graphical record (Figure 1), this aurora was mainly seen southward with its northern edge reaching Orion, as long as Trouvelot himself emphasized (see Figure 2), whereas Figure 1 shows aurora in the northern sky. Therefore, although Trouvelot had certainly seen the aurora on 4 February 1872, his auroral report at that time is hardly consistent with his drawing (Figure 1) and hence casts serious doubts on Kataoka *et al*.'s re-dating for Trouvelot's drawing.

We have also computed the star positions seen from Harvard College Observatory with Stellarium 0.19.3. The relative positions of the polar star, Ursa Major, and Cassiopeia certainly appear more favorable to 4 February rather than 1 March, if we fix the observational time as 21:25 LT, as suggested in Kataoka *et al*. (2019). However, Trouvelot's mention of Arcturus directly contradicts this conventional dating alteration in Kataoka *et al*. (2019). Trouvelot (1882, p. 161) states in his explanation, "The large star at some distance above the horizon on the right is Arcturus". Simulations with Stellarium show Arcturus at 21:25 is visible only after 9 February 1872. Therefore, Trouvelot's drawing cannot be dated as of February 4 – 6, but likely depicted as 1 March 1872 after the rise of Arcturus (20:02 on 1 March 1872). We note here that the reported observational time could be slightly different. This is not something extremely surprising as such detailed drawing must have taken substantial time to complete. Therefore, we conclude that Trouvelot's dating should be accepted as face value, rather than altered version as 4 – 6 February presented in Kataoka *et al*. (2019).

Moreover, other reports of simultaneous auroral observations seem to robustly advocate Trouvelot's original dating. Greely (1881, p. 74) confirms that aurorae were reported at "Buffalo, Burlington, Chicago, Cleveland, Detroit, Duluth, Escanaba, Grand Haven, Marquette, Oswego, Portland, ME, Toledo, Vicksburgh" on 1 March 1872. This description shows that the aurorae were witnessed throughout the northeastern part of the United States on 1 March 1872 and robustly agrees with the original dating of Trouvelot's auroral drawing. On the other hand, we have only two reports on 5 February and none on February 6 according to Greely (1881, p. 74). In this sense, the conventional date alteration to 5 – 6 February 1872 does not agree with the large auroral extension in Trouvelot's drawing either.

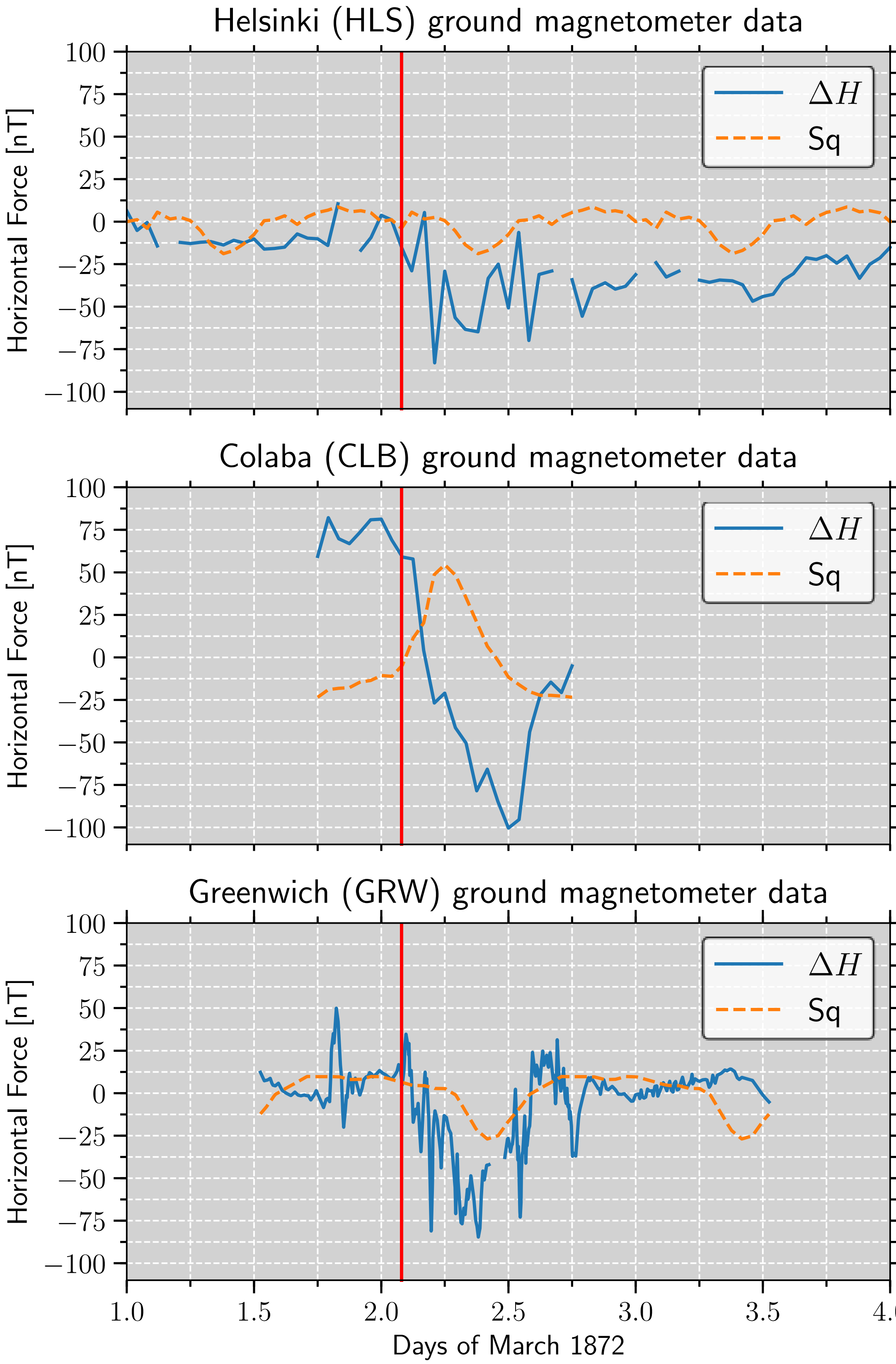
The star positions are very useful to understand the extent of the aurora in the night sky. Additionally, at the time of this observation, the Moon was below the horizon and this condition might have provided better auroral visibility. The pole star is at an elevation of ~ 42° which is equivalent to the geographical latitude of the observation site, Harvard College Observatory (N42°23′, W071°08′). The topmost star was seen above the Big dipper in the painting is Muscida, which had an altitude of ≈ 71° from the horizon at 21:25 LT on 1 March 1872. This implies the aurora was seen beyond 42° and possibly up to 71° in the elevation angle. Accordingly, the magnetic footprint of the equatorward boundary of the auroral oval is estimated to be 56.2° − 58.5° magnetic latitude (see O'Brien *et al*., 1962; Figure 2 of Hayakawa *et al*., 2018c), assuming the auroral elevation as ~400 km and the aurora is along the dipole magnetic field line (Roach *et al*., 1960; Ebihara *et al*., 2017).

4. Magnetic Measurements on 1 – 2 March 1872

One puzzling aspect of Trouvelot's auroral drawing (Figure 1) remains, in that "no magnetic storm was recorded" for 1 March 1872 (Kataoka *et al*., 2019). Indeed, Trouvelot's dating (1 March) shows quiet to moderate geomagnetic activity as indicated by its daily *aa* index = 13.2, (Mayaud, 1972), or its revised daily *aa* index = 11.2 (Lockwood et al., 2018). Applying Silverman (2003)'s threshold (*aa* ≤ 55), we can certainly categorize the geomagnetic activity on 1 March as quiet to moderate. Therefore, the aurora in Trouvelot's drawing have apparently occurred without significant magnetic storm and we have no other choice to classify this aurora as a "sporadic aurora", namely mid- to low-latitude aurorae during periods of quiet to moderate geomagnetic activity, as defined in Silverman (2003).

However, we need to emphasize that Trouvelot's observation was recorded in local time and need to take the offsets with Greenwich Mean Time (GMT) into consideration. Based on his observational site at Harvard College Observatory (N42°23′, W071°08′), we need to modify the observational time of 21:25 (with potential variation from 20:02) to GMT, in order to chronologically compare his observation with *aa* indices. As the time zone was introduced only after 1882, the observational time was most likely recorded in the local mean time (see also Silverman, 1998; Boteler, 2006a, 2006b). For Harvard College observatory, this means we apply a time-shift of UT -04:45. Therefore, we estimate the observational time in GMT as ≈ 02:10 (potentially ranging from 00:47) on 2 March 1872. Consulting traditional and revised

Aa indices on 2 March 1872, we found that the geomagnetic activity was much more enhanced as compared to 1 March 1872 (78.3 and 69.8; see Mayaud, 1972; Lockwood *et al*., 2018a, 2018b) and this puts Trouvelot's aurora as having occurred on a day beyond the threshold of sporadic aurora (Aa = 55) of Silverman (2003).



Helsinki (HLS) ground magnetometer data
Colaba (CLB) ground magnetometer data
Greenwich (GRW) ground magnetometer data
Horizontal Force [nT]
Days of March 1872
ΔH
Sq

Figure 4: Magnetic field variation observed at Helsinki, Colaba and Greenwich observatories during 1-3 March 1872. The solid blue curve represents quiet time subtracted horizontal (H) magnetic field component during the event. The dashed orange line shows the average diurnal Sq magnetic field variation of H-component during the five quietest days of March 1872, and the vertical red line indicates the time of Trouvelot's auroral drawing (02:10 GMT). A +12 hour time-shift was applied to the Greenwich Sq data, to convert its astronomical time to the civil time.

This interpretation is consistent with the difference of daily Ak index (9 *v.s.* 45) derived from the Helsinki Observatory (Nevanlinna and Kataja, 1993) and further supported by the hourly measurements at Helsinki on its basis (Nevanlinna *et al.*, 1992; Nevanlinna & Ketola, 1993; Nevanlinna, 2004, 2006). At the time of Trouvelot's auroral observation, Helsinki Observatory (N61°10′, E24°59′; 57.8° MLAT) operated a regular magnetic observation. Helsinki Observatory is quite favorably situated for our comparison with the auroral observation at Harvard College Observatory, as both Harvard College Observatory and Helsinki Observatory are geomagnetically located in sub-auroral zones (53.8° v.s. 57.8° MLAT) due to the contemporary position of the north magnetic pole, despite their variation of ~ 20° in geographical latitudes. Helsinki H-values are based on visual spot readings eye-telescope-mirror-scale-method that was in use in many magnetic observatories during the 19th century as in Rome in 1859 (see, Blake *et al.*, 2020). The hourly values of H consisted of three consecutive observations with 30-sec interval centered on the full hour. The final value for each hour was the mean value of these three readings (Nevanlinna et al., 1992; Nevanlinna & Ketola, 1993; Nevanlinna, 2004, 2006), while this procedure often averages out the storm amplitude in comparison with those in spot value (Viljanen *et al.*, 2014).

The magnetic measurements at Helsinki (see Nevanlinna, 2004, 2006) show that the recorded timing of auroral observation corresponded to a short negative excursion of ≈ 20 nT, followed by two other large negative excursions as depicted in the solid blue line of Figure 4 (upper panel). For comparison, Figure 4 shows the average magnetic field variation of H-component (dashed orange line) during the five quietest days of the month, selected with the revised *aa* index (Lockwood *et al*., 2018). It clearly shows that there was a geomagnetic disturbance at the time of Trouvelot's auroral drawing (Figure 1). Later that day, the magnetic field shows a sharp decrease (≈ −85 nT) and then a steady and slow recovery over the next few days at Helsinki, which hints at the geomagnetic storm condition.

We also compare this insight with Greenwich magnetograms (N51°29′, E000°00′; 54.6° MLAT) at that time (Figure 4, bottom panel). Their chronologies are shown with astronomical time (add 12h to get civil time) and these values were multiplied by -1, to account for the orientation of the magnetogram (see Boteler, 2006a, 2006b; Cliver, 2006; Clarke *et al*., 2010). As its scale is given "the movement of the spot of light for 0.01 part of the whole horizontal force is 2.361 inches", we compute 2.361 inches = 59.964 mm = 0.01 H_total. The H_total corresponds to ≈ 17469 nT, according to the GUFM1 model (Jackson *et al*., 2000). As this magnetogram has a mm scale, we convert the original magnetogram to the modern unit, based on the scale of 1 mm = 2.9 nT. Its daily Sq variation is reconstructed from the RGO yearbook (RGO, 1872, p. xxix), and a comparison with a modern Sq variation from the Hartland INTERMAGNET site indicates that these values were recorded in astronomical time. As such, Greenwich magnetogram shows its ΔH amplitude of ≈ 167 nT.

The Greenwich magnetograms in the H-component display the negative excursion confirming the presence of a geomagnetic storm also noted in the Helsinki magnetogram.

Around 19:30 GMT a sharp increase is seen in the H-component of the geomagnetic field variations (note that variations in magnetogram are inverted). A similar enhancement is observed in Helsinki magnetic field variations (Figure 5). This could be related to the sudden impulse (SI^+), which is generally associated with high solar wind dynamic pressure enhancements (Joselyn & Tsurutani, 1990; Oliveira & Samsonov, 2018; Rudd *et al*., 2019). The H-component of the magnetic variation started to decrease at ~02:20 GMT. The magnetic variation has two negative peaks at ≈ 04:40 GMT and ≈ 09:00 GMT, which probably agrees with the two spikes at Helsinki magnetograms.

Additionally, a geomagnetic disturbance was registered at the Bombay (modern-day Colaba; N18°56′, E072°50′; 10.0° MLAT) magnetic observatory for the 1 March (Moos, 1910b, p. 452; pp. 480 – 481; see central panel of Figure 4) as part of a summary table listing notable events. This table registers the SI^+ at Colaba at ~ 0:00 LT on 2 March 1872, that is ~ 19:09 GMT on 1 March 1872 (with the time difference of UT + 04:51), and record amplitude of its horizontal range as ≈ 195 nT with its minimum ≈ 02:17 LMT (≈ 07:08 GMT) on 2 March. After removing their Sq variation (Moos, 1910a, p. 64), we observe the ΔH amplitude as ≈ 185 nT.

According to Oliveira *et al*. (2018), interplanetary shocks can further intensify the low and equatorial magnetic field response if they strike the magnetosphere with small impact angles and high speeds, as shown by simulations and observations (*e.g*., Oliveira & Samsonov, 2018; Rudd *et al*., 2019). This scenario is consistent with both possibilities of shock driving by CMEs and CIRs. However, if the large daily magnetic field amplitude at Colaba was followed by a CIR-driven shock, the corresponding CIR was most likely associated with a high-speed and high-density solar wind stream. Additionally, this is supported by the occurrence of mid-latitude and bright aurorae located around the midnight sector after the onset of CIRs during the declining phase of solar cycle 23 (Luan *et al*., 2013), which is favored by darkness and winter conditions (Newell *et al*., 1996; Shue *et al*., 2002). These CIR-caused aurorae are typically associated with pre-conditions of IMF Bz < 0 before the CIR onset (*e.g*., Zhou & Tsurutani, 2001; Luan *et al*., 2013), which was probably the scenario associated with the driver of Trouvelot's aurora.

On their basis, we locate Trouvelot's auroral observation during the initial phase of this storm. We interpret this as a result of a strong compression of the magnetosphere by an interplanetary shock leading to the triggering of substorms in the nightside magnetosphere (Tsurutani & Zhou, 2003; Yue *et al.*, 2010; Oliveira & Raeder, 2015). This may imply that the compression of the magnetosphere by an interplanetary shock/pressure pulse could have triggered a substorm and then manifested the said auroral display.

5. Possible Recurrent Magnetic Activity at that Time

This work has confirmed the occurrence of a great auroral display and a short magnetic storm on 2 March 1872. Bernaerts' sunspot drawing on 28 February 1872 (Figure 5) confirms one large and complex sunspot group and four more moderate sunspot groups near the disk center. Given their geo-effective position, it is possible that one of these groups to have triggered the source disturbance for this storm and aurora.

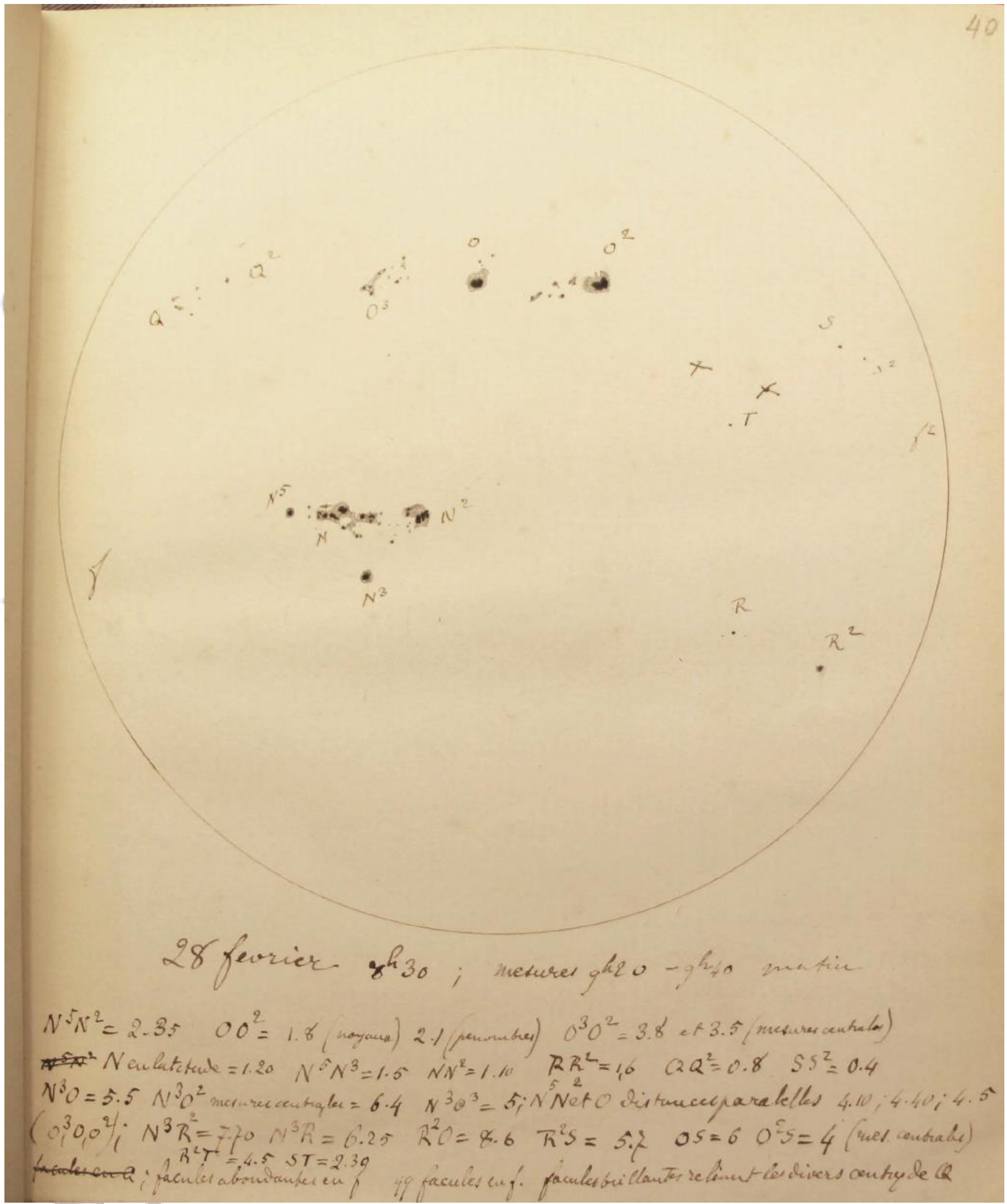
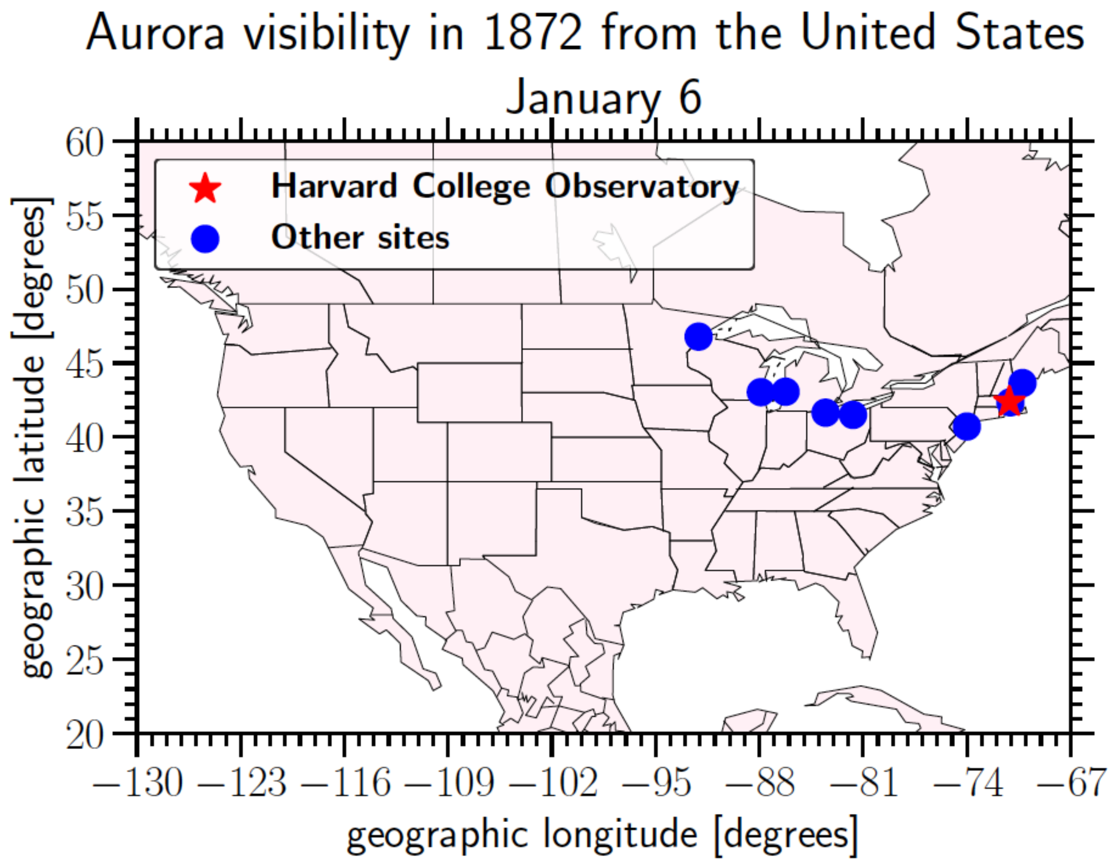


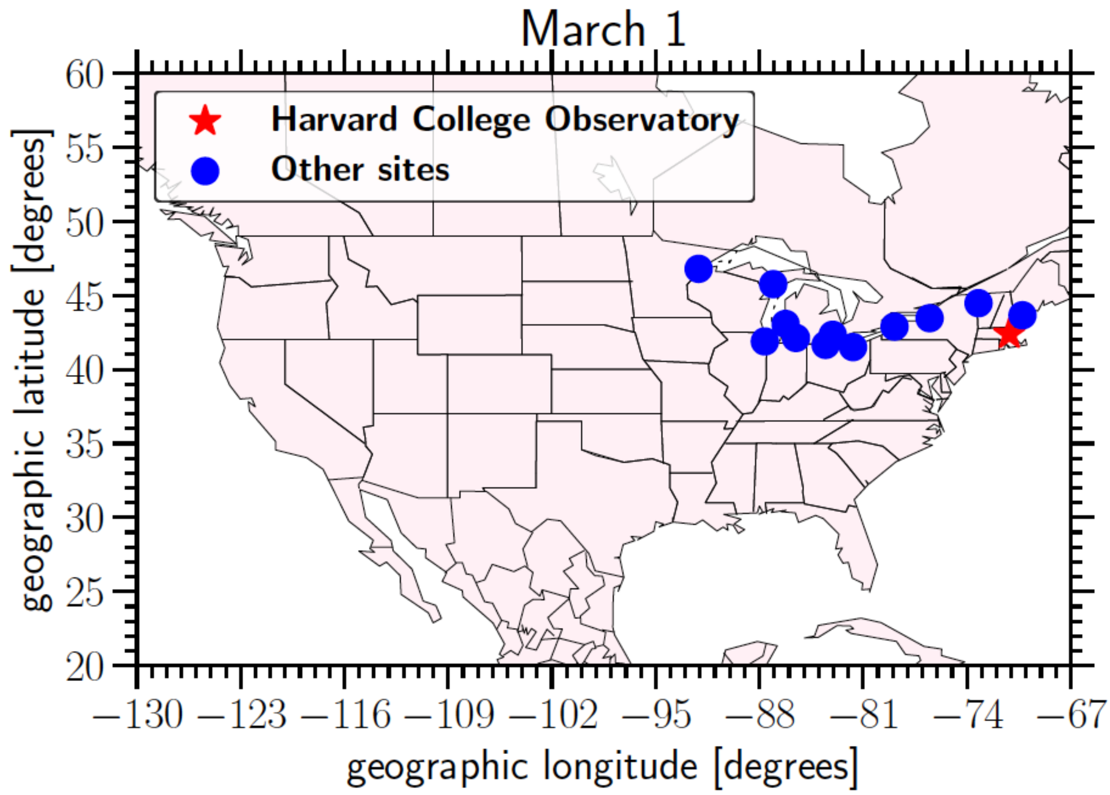
Figure 5: Bernaerts' sunspot drawing on 28 February 1872 (MSS Bernarts, 3, v. 3, f. 40), courtesy of the Royal Astronomical Society. One large complex sunspot group is located near the solar disk center along with other moderate sunspot groups.

Interestingly, there have been earlier reports of aurorae on 6 January 1872 (Trouvelot, 1882, p. 30) and 4 February (Tsurutani et al., 2005; Silverman, 2008; Hayakawa et al., 2018a). The

January aurora is simultaneously reported in “Boston, Cleveland, Duluth, Grand Haven, Milwaukee, New York, Portland, ME, Toledo” (Greely, 1881, p. 74). As summarized in Figure 6, these auroral displays widely covered the New England region. In addition, disturbances to the horizontal geomagnetic field were registered for 6 January (≈ 107 nT), 4 February (≈ 1023 nT) and 2 March (≈ 195 nT) at the Colaba observatory (Moos, 1910b, p. 452).



Aurora visibility in 1872 from the United States
January 6
Harvard College Observatory
Other sites
geographic latitude [degrees]
60
55
50
45
40
35
30
25
20
−130 −123 −116 −109 −102 −95 −88 −81 −74 −67
geographic longitude [degrees]



March 1
Harvard College Observatory
Other sites
geographic latitude [degrees]
60
55
50
45
40
35
30
25
20
−130 −123 −116 −109 −102 −95 −88 −81 −74 −67
geographic longitude [degrees]

Figure 6: Auroral displays on 6 January (top panel) and 1 March (bottom panel) in 1872 in the United States according to Trouvelot (1882) and Greely (1881). Harvard College Observatory is shown in a red star and other sites are shown in blue circles. The dates are shown in LT.

The occurrence intervals of all these auroral observations and geomagnetic disturbances are consistent with the duration of solar rotation (≈ 27 days.) and may indicate recurrent geomagnetic activity in early 1872, as inferred from the modern scientific literature (see *e.g.*, Burlaga & Lepping, 1977; Baker *et al*., 1997; Willis and Stephenson, 2001; Tsurutani *et al*., 2006a, 2006b; Willis & Davis, 2014). Further simultaneous auroral reports confirm the occurrences of these recurrent storms. European records show auroral reports in Norwegian cities (Tromholt, 1902, p. 242) for the 6/7 January storm; and those in Norwegian cities (Tromholt, 1902, p. 246), Swedish cities (Rubenson, 1882, p. 184), Ösel Island (current Saaremaa Island, the largest island in the Gulf of Riga) in Estonia (Heis, 1872, p. 339), and even down to Florence (Denza, 1872, p. 827) for the 1/2 March storm. These European observations may have formed an arc with the auroral observations in the Northern part of the United States, while they may have fallen in different phases of the same storm.

Modern observations show that such a "clock-like" recurrent geomagnetic activity is generally caused by coronal holes and high-speed streams. As viewed from the Earth, coronal holes act as rigid rotators and keep reappearing at ≈ 27-day intervals, due to the rotation of the Sun (Tsurutani *et al*., 1982; Lefevre *et al*., 2016). High-speed solar-wind streams with peak speeds of ≈ 750 – 800 km/s emanate from these coronal holes (McComas *et al*., 2002). The high-speed streams interact with the upstream slow-speed solar-wind streams, forming compressive Corotating Interaction Regions (CIRs) (Smith & Wolfe, 1976; Tsurutani &

Gonzalez, 1987; Tsurutani *et al*., 1995; Richardson *et al*., 2006). CIRs can have a forward shock at the antisolar edge. When the CIR-driven shock impinges on the terrestrial magnetosphere, it may be able to trigger a substorm causing nightside aurorae as if the ICME-driven shock can do (Zhou & Tsurutani 2001; Tsurutani & Zhou, 2003; Hajra & Tsurutani 2018).

At the same time, Richardson *et al*. (2006) in their study of CIR magnetic storms from 1972 to 2005 found a maximum storm intensity of Dst = −161 nT. Meng *et al*. (2019) have studied all extreme storms with Dst < −250 nT from 1957 to 2019 and have not found CIR-storms of that intensity. Therefore we conclude that the February 1872 storm was most probably caused by ICME impact, based on its auroral visibility even down to Bombay (Tsurutani *et al*., 2005; Silverman, 2008; Hayakawa *et al*., 2018a).

As such, it is plausible to explain these recurrent aurorae with a combination of ICMEs and CIR shocks. Further, it is known for coronal holes to be located at the place of decayed active region (Karachik *et al*. 2010). The interplanetary high-speed stream originated from the already co-existing or newly formed coronal holes from the decayed active regions that could not be seen in the visible light back in 1872. CIRs typically cause weak magnetic storms to no storms at all (Tsurutani *et al*., 1995, 2006). This is in good agreement with the auroral reports with apparent moderate geomagnetic activities on 6 January and 2 March (Figures 3 and 7). Meanwhile, the cause of Trouvelot's aurora on 2 March 1872 still remains controversial, as (i) the CIR shocks at 1 au are not frequent (Borovsky & Denton, 2006; Tsurutani et al., 2006), while we should also reserve possibilities for CIRs bounded by strong shocks. (ii) the storm amplitude recorded at the low-latitude magnetic observatory, Colaba, reached ≈ 195 nT (Moos, 1910b, p. 452), and (iii) the storm recovery looks faster than typical CIR storms (Figures 4 and 5; see also Borovsky & Denton, 2006; Tsurutani *et al*., 2018).

Generally, recurrent geomagnetic activity is associated with CIRs, however for transients to be responsible for the recurrent geomagnetic activity, the Sun needs to eject a continuous stream of transients from a fixed location. It is unlikely to observe this scenario, whereas Crooker and McAllister (1997) have reported such a scenario as a cause of recurrent large magnitude storms. Also, the amplitude of the reported storm in our study is not small, but still within the extent of reported CIR induced storms (O'Brien & McPherron, 2000; Richardson *et al*., 2006). It is therefore conservative to reserve both CIRs and ICMEs for its possible cause.

The sequence of observed aurorae on 4 – 6 February is more plausibly caused with the CIRs after great ICMEs (cause of the 4 February storm) as the magnetic activity became rather moderate after 5 February (Figure 3) and single ICMEs cause aurorae only for few hours (Lakhina *et al*., 2013; Lakhina & Tsurutani, 2017). Therefore, the February sequence could be considered as a combination of intense ICMEs and high-speed streams following the CIRs resulting in high-intensity long-duration continuous AE activities (HILDCAAs) (Tsurutanu and Gonzalez 1987; Tsurutani *et al*., 1995, 2006; Kozyra *et al*., 2006; Turner *et al*., 2006; Hajra *et al*., 2014).

5. Discussion and Conclusion

Our analysis of Trouvelot's aurora record dated on 1 March 1872 confirms that his aurora was indeed observed on that day, removing earlier doubt on his original dating. The manipulated dating proposed by Kataoka *et al*. (2019) contradicts Trouvelot's own observation (see Figure 2) and the original dating is robustly supported with the simultaneous auroral observations. Moreover, by investigating the star positions from Trouvelot's drawing and the simulated star charts, we have confirmed the date and time of the auroral observations. Astronomical records have been very important in dating historical events. This event was one such case. The star positions painted along with the aurora by the astronomer Trouvelot were of paramount importance for us to use them to confirm the original dating.

While the magnetic activity was moderate on 1 March 1872 according to the daily Aa index, the location of its observational site requires us to take the time difference with respect to GMT. On this basis, this aurora fell on 2 March 1872 in GMT and its geomagnetic activity was slightly more notable. Moreover, the ground magnetograms with more than hourly resolution showed that there was a short geomagnetic storm during this period, and a relatively moderate geomagnetic disturbance was also registered at Colaba for this time-period. The aurora occurred during the initial phase of the storm and hence may have been associated with a substorm event most likely triggered by the compression of the magnetosphere by a moderate/strong interplanetary shock (*e.g.*, Oliveira & Samsonov, 2018). Shiokawa *et al*. (2005) have shown that low-latitude aurorae were observed at Rikubetsu (34.7° magnetic latitude) in Japan not only during the storm main phase but also during the initial phase.

This result implies that a short magnetic storm may have been smeared out by the daily Aa index due to its short duration and the time difference. As the existing sporadic aurorae were investigated with a threshold of *daily* Aa index ≤ 55 (Silverman, 2003; Willis *et al*., 2007),there are probably more than a few events whose magnetic disturbance was overlooked because of these two reasons. Therefore, the geomagnetic profiles of the reported historical sporadic aurorae need further investigations using such high-time resolution geomagnetic field data and the observational metadata, if available, to compare with their detailed descriptions and to see possible contributions of supersubstorms (see *e.g.*, Hajra *et al*., 2016; Hajra & Tsurutani, 2018).

Additionally, the investigated aurora appears to be associated with the other mid-latitude aurorae on 6 January and 4 – 6 February, given their intervals of ≈ 27 days. This sequence indicates recurrent solar activity caused with a combination of CIRs and CMEs. This documented historic event shows that even moderate geomagnetic activity can trigger visual aurorae in mid-latitudes. The relevance of these observations has space-weather implications, as combinations of CIRs and ICMEs could be responsible for periodically observed historic intense/moderate geomagnetic activity events.

Data Availability

Trouvelot's auroral drawing and Bernaerts' sunspot drawing are preserved in the archives of the New York Public Library and the Royal Astronomical Society. The magnetic measurements at Greenwich, Helsinki, and Colaba are available at the British Geological Survey (BGS), the Finnish Meteorological Institute, and Moos (1910a, 1910b), respectively. The American auroral visibility reports in 1872 are available at Greely (1881).

Acknowledgment

HH thanks New York Public Library and the Royal Astronomical Society (especially Sian Prosser) for providing images of Trouvelot's auroral drawing and Bernaerts' sunspot drawing. We thank British Geological Survey (BGS) for providing the Greenwich magnetograms, and WDC for Geomagnetism at Kyoto and the Finnish Meteorological Institute (https://space.fmi.fi/MAGN/magn/Helsinki/H/H.tables/H1872vk.lis) for providing the Helsinki magnetic field data. We thank Colaba Observatory (now administrated by Indian Institute of Geomagnetism, India), Helsinki Observatory, and Greenwich Observatory for the recording of magnetic field measurements. AB is supported by funding from Van Allen Probes Mission and HH is supported by Young Leader Cultivation (YLC) program of Nagoya University, the 2019 Collaborative Research Grants for YLC (grant # YLC2019A02), the Unit of Synergetic Studies for Space of Kyoto University, BroadBand Tower, and JSPS grant-in-aids (JP15H05812 and JP15H05816). SPB is supported by the NASA's Living With a Star program (17-624 LWS17 2-0042). HH and SMS thank Rachel Rosenblum for her valuable help, considerations, and arrangements during their discussions. The Greenwich magnetogram was digitised using the WebPlotDigitizer software (automeris.io/WebPlotDigitizer).

References

Akasofu, S.-I. (1964). The development of auroral substorms, *Planetary and Space Science.* 12, 273-282. https://doi.org/10.1016.0032-0633(64)90151-5

Allen, J., Frank, L., Sauer, H., Reiff, P. (1989), Effects of the March 1989 solar activity. *Eos, Transactions American Geophysical Union,* 70, 1479-1488. https://doi.org/10.1029/89EO00409

Baker, D. N., Li, X., Turner, N., *et al*. (1997). Recurrent geomagnetic storms and relativistic electron enhancements in the outer magnetosphere: ISTP coordinated measurements. *Journal of Geophysical Research.* 102, A7, 14141-14148. https://doi.org/10.1029/97JA00565

Blake, S. P, Pulkkinen, A., Schuck, P. W., Nevanlinna, H., Reale, O., Veenadhari, B., Mukherjee, S. (2020). Magnetic Field Measurements from Rome during the August-

September 1859 Storms. *Journal of Geophysical Research: Space Physics.* 125. https://doi.org/10.1029/2019JA027336

Borovsky, J. E., & Denton, M. H. (2006). Differences between CME-driven storms and CIR-driven storms. *Journal of Geophysical Research: Space Physics.* 111, A7, A07S08. https://doi.org/10.1029/2005JA011447

Boteler, D. H. (2006a). The super storms of August/September 1859 and their effects on the telegraph system. *Advances in Space Research.* 38, 159-172. https://doi.org/ 10.1016/j.asr.2006.01.013

Boteler, D. H. (2006b). Comment on time conventions in the recordings of 1859. *Advances in Space Research.* 38, 301-303. https://doi.org/10.1016/j.asr.2006.07.006

Boteler, D. H.: 2019, A 21st Century View of the March 1989 Magnetic Storm. *Space Weather.* 17, 1427-1441. https://doi.org/10.1029/2019SW002278

Burlaga, L. F., Lepping, R. P. (1977). The causes of recurrent geomagnetic storms. *Planetary and Space Science.* 25, 1151-1160. https://doi.org/10.1016/0032-0633(77)90090-3

Cid, C., Palacios, J., Saiz, E., Guerrero, A., Cerrato, Y. (2014). On extreme geomagnetic storms. *Journal of Space Weather and Space Climate.* 4, A28. DOI: 10.1051/swsc/2014026

Cid, C., Saiz, E., Guerrero, A., Palacios, J., Cerrato, Y. (2015) A Carrington-like geomagnetic storm observed in the 21st century. *Journal of Space Weather and Space Climate.* 5, A16. DOI: 10.1051/swsc/2015017

Clarke, E., Rodger, C., Clilverd, M., Humphries, T., Baillie, O., Thomson, A. (2010). An estimation of the Carrington flare magnitude from solar flare effects (sfe) in the geomagnetic records. In: *RAS NAM 2010 with the UK Solar Physics & MIST Meeting*, Glasgow. Scotland. http://nora.nerc.ac.uk/id/eprint/19904/

Cliver, E. W. (2006). The 1859 space weather event: Then and now, *Advances in Space Research*, 38, 119-129. DOI: 10.1016/j.asr.2005.07.077

Cliver, E. W., Dietrich, W. F. (2013). The 1859 space weather event revisited: limits of extreme activity. *Journal of Space Weather and Space Climate.* 3, A31. DOI: 10.1051/swsc/2013053

Crooker, N. U., McAllister H. A. (1997). Transients associated with recurrent storms. *Journal of Geophysical Research: Space Physics.* 102, A7, 14041-14047.

Davis, T. N., Sugiura, M. (1966). Auroral electrojet activity index AE and its universal time variations. *Journal of Geophysical Research.* 71, 785–801.

Daglis, I. A., Thorne, R. M., Baumjohann, W., Orsini, S. (1999) The terrestrial ring current: Origin, formation, and decay. *Reviews of Geophysics.* 37, 407-438. DOI: 10.1029/1999RG900009

Denza, P. (1872). Pluie de sable et phénomènes cosmiques observés en Italie dans la première décade de mars 1872. Note du P. Denza, directeur de l'Observatoire de Moncalieri, *Comptes Rendus.* 74, 826-828.

Domínguez-Castro, F., Vaquero, J. M., Bertolin, C., Gallego, M.-C., De la Guía, C., Camuffo, D. (2016). Aurorae observed by Giuseppe Toaldo in Padua (1766-1797). *Journal of Space Weather and Space Climate.* 6, A21. DOI: 10.1051/swsc/2016016

Ebihara, Y., Hayakawa, H., Iwahashi, K., Tamazawa, H., Kawamura, A. D., Isobe, H. (2017). Possible Cause of Extremely Bright Aurora Witnessed in East Asia on 17 September 1770. *Space Weather.* 15, 1373-1382. DOI: 10.1002/2017SW001693

Gonzalez, W. D., Joselyn, J. A., Kamide, Y., Kroehl, H. W., Rostoker, G., Tsurutani, B. T., Vasyliunas, V. M. (1994). What is a geomagnetic storm? *Journal of Geophysical Research.* 99, A4, 5771-5792. https://doi.org/10.1029/93JA02867

Gonzalez, W. D., Tsurutani, B. T., McIntosh, P. S., Clúa de Gonzalez, A. L. (1996). Coronal hole-active region-Current sheet (CHARCS) Association with intense interplanetary and geomagnetic activity. *Geophysical Research Letters.* 23, 2577-2580. DOI: 10.1029/96GL02393

Gonzalez, W. D., Echer, E., Tsurutani, B. T., Clúa de Gonzalez, A. L., Dal Lago, A. (2011). Interplanetary Origin of Intense, Superintense and Extreme Geomagnetic Storms. *Space Science Reviews.* 158, 69-89. DOI: 10.1007/s11214-010-9715-2

Greely, A. W. (1881) *Chronological Lists of Auroras Observed from 1870 to 1879*, Washington DC, Government Printing Office.

Hajra, R., Echer, E., Tsurutani, B. T., Gonzalez, W. D. (2014). Solar wind-magnetosphere energy coupling efficiency and partitioning: HILDCAAs and preceding CIR storms during solar cycle 23. *Journal of Geophysical Research: Space Physics.* 119, 2675-2690. DOI: 10.1002/2013JA019646

Hajra, R., Tsurutani, B. T., Echer, E., Gonzalez, W. D., Gjerloev, J. W. (2016). Supersubstorms (SML < -2500 nT): Magnetic storm and solar cycle dependences. *Journal of Geophysical Research: Space Physics.* 121, 7805-7816. DOI: 10.1002/2015JA021835

Hajra, R., Tsurutani, B. T. (2018). Interplanetary Shocks Inducing Magnetospheric Supersubstorms (SML < -2500 nT): Unusual Auroral Morphologies and Energy Flow. *The Astrophysical Journal.* 858, 123. DOI: 10.3847/1538-4357/aabaed

Hale, G. E. (1895). Etienne-Leopold Trouvelot. *Astrophysical Journal.* 2, 166-167. DOI: 10.1086/140125

Hapgood, M. (2019). The Great Storm of May 1921: An Exemplar of a Dangerous Space Weather Event. *Space Weather.* 17, 950-975. DOI:10.1029/2019SW002195

Hayakawa, H., Ebihara, Y., Willis, D. M., *et al*. (2018a). The Great Space Weather Event during 1872 February Recorded in East Asia. *The Astrophysical Journal.* 862, 15, DOI:10.3847/1538-4357/aaca40

Hayakawa, H., Vaquero, J. M., Ebihara, Y. (2018b). Sporadic auroras near the geomagnetic equator: in the Philippines, on 27 October 1856. *Annales Geophysicae*. 36, 1153-1160. DOI: 10.5194/angeo-36-1153-2018

Hayakawa, H., Ebihara, Y., Hand, D. P., Hayakawa, S., Kumar, S., Mukherjee, S., Veenadhari, B. (2018c). Low-latitude Aurorae during the Extreme Space Weather Events in 1859. *The Astrophysical Journal*. 869, 57, DOI: 10.3847/1538-4357/aae47c

Hayakawa, H., Ebihara, Y., Cliver, E. W., *et al*. (2019a). The extreme space weather event in September 1909. *Monthly Notices of the Royal Astronomical Society*. 484, 4083-4099. DOI: 10.1093/mnras/sty319

Hayakawa, H., Ebihara, Y., Willis, D. M., *et al*. (2019b). Temporal and Spatial Evolutions of a Large Sunspot Group and Great Auroral Storms around the Carrington Event in 1859. *Space Weather*. DOI: 10.1029/2019SW002269

Hayakawa, H., Mitsuma, Y., Ebihara, Y., Miyake, F. (2019c). The Earliest Candidates of Auroral Observations in Assyrian Astrological Reports: Insights on Solar Activity around 660 BCE. *The Astrophysical Journal Letters*. 884, L18. DOI: 10.3847/2041-8213/ab42e4

Hayakawa, H., *et al*. (2020a), The Extreme Space Weather Event in 1903 October/November: An Outburst from the Quiet Sun. *The Astrophysical Journal Letters*. DOI: 10.3847/2041-8213/ab6a18

Hayakawa, H., Ebihara, Y., Pevtsov, A. A., Bhaskar, A., Karachik, N., Oliveira, D. M. (2020b) Intensity and Time Series of Extreme Solar-Terrestrial Storm in March 1946, *Monthly Notices of the Royal Astronomical Society*, DOI: 10.1093/mnras/staa1508

Heis, E. (1872). *Wochenschrift für Astronomie, Meteorologie und Geographie*. v.1872, Halle, H. W. Schmidt.

Jackson, A., Jonkers, A. R. T., Walker, M. R. (2000). Four centuries of geomagnetic secular variation from historical records. *Roy. Soc. of London Phil. Tr. A.* 358, 957, DOI: 10.1098/rsta.2000.0569

Joselyn, J. A., Tsurutani, B. T. (1990). Geomagnetic Sudden impulses and storm sudden commencements: A note on terminology. *Eos, Transactions American Geophysical Union.* 71, 1808-1809. DOI: 10.1029/90EO00350

Karachik, N. V., Pevtsov, A. A., Abramenko, V. I. (2010). Formation of coronal holes on the ashes of active regions. *The Astrophysical Journal.* 714, 2, 1672, DOI: 10.1088/0004-637X/714/2/1672

Kataoka, R., Uchino, S., Fujiwara, Y., Fujita, S., Yamamoto, K. (2019). Fan-shaped aurora as seen from Japan during a great magnetic storm on February 11, 1958. *Journal of Space Weather and Space Climate.* 9, A16, DOI: 10.1051/swsc/2019013

Kozyra, J. U., *et al*. (2006). Response of the Upper/Middle Atmosphere to Coronal Holes and Powerful High-Speed Solar Wind Streams in 2003, *Recurrent Magnetic Storms: Corotating Solar Wind Streams*. Geophysical Monograph 167 (Eds. B. Tsurutani, R. McPherron, W. Gonzalez, G. Lu, J. H. A. Sobral, and N. Gopalswamy). ISBN-13: 978-0-87590-432-0. Published by the AGU Books Board, AGU, Washington, DC USA, 2006, p.319. DOI: 10.1029/167GM24

Lakhina, G. S., Alex, S., Tsurutani, B. T. and Gonzalez, W. D. (2013). Supermagnetic Storms: Hazard to Society. In: *Extreme Events and Natural Hazards: The Complexity Perspective* (eds. A.S. Sharma, A. Bunde, V.P. Dimri and D.N. Baker). DOI: 10.1029/2011GM001073

Lakhina, G. S., Tsurutani, B. T. (2017). Supergeomagnetic Storms: Past, Present, and Future, in: *Extreme Events in Geospace* (ed. N. Buzulukova), pp.157-185. DOI: 10.1016/B978-0-12-812700-1.00007-8

Lakhina, G. S., Tsurutani, B. T. (2018). Supergeomagnetic Storms: Past, Present, and Future, in: Buzulukova, N. (ed.) *Extreme Events in Geospace*, pp.157-185. DOI: 10.1016/B978-0-12-812700-1.00007-8

Lefèvre, L., Vennerstrøm, S., Dumbović, M., Vršnak, B., Sudar, D., Arlt, R., Clette, F., Crosby, N. (2016), Detailed Analysis of Solar Data Related to Historical Extreme Geomagnetic Storms: 1868 – 2010. *Solar Physics.* 291, 1483-1531. DOI: 10.1007/s11207-016-0892-3

Liu, Y. D., Zhao, X., Hu, H., Vourlidas, A., Zhu, B. (2019), A Comparative Study of 2017 July and 2012 July Complex Eruptions: Are Solar Superstorms "Perfect Storms" in Nature?. *The Astrophysical Journal Supplement Series.* 241, 15. DOI: 10.3847/1538-4365/ab0649

Lockwood, M., Barnard, L. (2015). An arch in the UK: a new catalogue of auroral observations made in the British Isles and Ireland. *Astrononmy and Geophysics.* 56, 25-30. DOI: 10.1093/astrogeo/atv132

Lockwood, M., Owens, M. J., Barnard, L., Scott, C. J., Usoskin, I. G., Nevanlinna, H. (2016). Tests of Sunspot Number Sequences: 2. Using Geomagnetic and Auroral Data. *Solar Physics.* 291, 2811-2828. DOI: 10.1007/s11207-016-0913-2

Lockwood, M., Chambodut, A., Barnard, L. A., Owens, M. J., Clarke, E., Mendel, V. (2018a). A homogeneous aa index: 1. Secular variation. *Journal of Space Weather and Space Climate.* 8, A53. DOI: 10.1051/swsc/2018038

Lockwood, M., Finch, I. D., Chambodut, A., Barnard, L. A., Owens, M. J., Clarke, E.: (2018b). A homogeneous aa index: 2. Hemispheric asymmetries and the equinoctial variation. *Journal of Space Weather and Space Climate.* 8, A58, DOI: 10.1051/swsc/2018044

Love, J. J., Hayakawa, H., Cliver, E. W. (2019a). On the Intensity of the Magnetic Superstorm of September 1909. *Space Weather.* 17, 37-45. DOI: 10.1029/2018SW002079

Love, J. J., Hayakawa, H., Cliver, E. W. (2019b). Intensity and impact of the New York Railroad superstorm of May 1921. *Space Weather.* 17, 1281-1292. DOI: 10.1029/2019SW002250

Luan, X., Wang, W., Lei, J., Burns, A., Dou, X., & Xu, J. (2013). Geomagnetic and auroral activity driven by corotating interaction regions during the declining phase of Solar Cycle 23. *Journal of Geophysical Research.* 118(3), 1255-1269. https://doi.org/10.1002/jgra.50195

Mayaud, P. N. (1972). The *aa* indices: A 100-year series characterizing the magnetic activity. *Journal of Geophysical Research.* 77, 6870, DOI: 10.1029/JA077i034p06870

McComas, D. J., Elliott, H. A., Gosling, J. T., Reisenfeld, D. B., Skoug, R. M., Goldstein, B. E., Neugebauer, M., Balogh, A. (2002). Ulysses' second fast-latitude scan: Complexity near solar maximum and the reformation of polar coronal holes. *Geophysical Research Letters.* 29, 9, 1290, DOI: 10.1029/2001GL014164

Meng, X., Tsurutani, B. T., Mannucci, A. J. (2019). The Solar and Interplanetary Causes of Superstorms (Minimum Dst ≤ -250 nT) During the Space Age. *Journal of Geophysical Research: Space Physics.* 124, 3926-3948. DOI: 10.1029/2018JA026425

Moos, N. A. F. (1910a) Magnetic observations made at the Government Observatory for the period 1846 to 1905 and their discussion by N.A.F. Moos. Part I. Magnetic data and instruments. Gov. Cent. Press, Bombay, India.

Moos, N. A. F. (1910b) *Magnetic Observations Made at the Government Observatory, Bombay, 1846-1905, Part II: The Phenomenon and Its Discussion.* Gov. Cent. Press, Bombay, India.

Nevanlinna, H., Ketola, A., Hakkinen, L., Viljanen, A., Ivory, K. (1992). *Magnetic results from Helsinki magneticmeteorological ob- servatory, Part II: Geomagnetic activity 1844–1856.* Finn. Met. Inst., Geophys. Publ. 30, 65.

Nevanlinna, H., Ketola, A. (1993). *Magnetic results from Helsinki magneticmeteorological observatory, Part III: Declination 1854– 1880, Geomagnetic activity 1844–1880.* Finn. Met. Inst., Geophys. Publ. 33, 193.

Nevanlinna, H., Kataja, E. (1993). An extension of the geomagnetic activity index series aa for two solar cycles (1844-1868). *Geophysical Research Letters.* 20, 2703-2706. DOI: 10.1029/93GL03001

Nevanlinna, H. (2004) Results of the Helsinki magnetic observatory 1844-1912. *Annales Geophysicae.* 22, 1691-1704. DOI: 10.5194/angeo-22-1691-2004

Nevanlinna, H. (2006). Historical Space Climate Data from Finland: Compilation and Analysis. *Solar Physics.* 224, 395-405. DOI: 10.1007/s11207-005-3749-8

Newell, P. T., Gjerloev, J. W. (2011),.Evaluation of SuperMAG auroral electrojet indices as indicators of substorms and auroral power. *Journal of Geophysical Researches.* 116, A12, doi: 10.1029/2011JA016779

O'Brien, B. J., *et al*. (1962). Measurements of the Intensity and Spectrum of Electrons at 1000-Kilometer Altitude and High Latitudes. *J. Geophys. Res.* 67, 4, 1209-1225. Doi: 10.1029/JZ067i004p01209

O'Brien, T. PP., McPherron, R. L. (2000) An empirical phase space analysis of ring current dynamics: Solar wind control of injection and decay. *Journal of Geophysical Research.* 105, A4, 7707-7720. DOI: 10.1029/1998JA000437

Odenwald, S. (2015) *Solar Storms: 2000 years of human calamity* (San Bernardino, Create Space), ISBN: 978-1-505-941463

Oliveira, D. M., Raeder, J. (2015) Impact angle control of interplanetary shock geoeffectiveness: A statistical study. *Journal of Geophysical Research: Space Physics.* 120, 4313–4323. https://doi.org/10.1002/2015JA021147.

Oliveira, D. M., & Samsonov, A. A. (2018) Geoeffectiveness of interplanetary shocks controlled by impact angles: A review. *Advances in Space Research.* 61, 1–44. https://doi.org/10.1016/j.asr.2017.10.006.

Oliveira, D. M., Arel, D., Raeder, J., Zesta, E., Ngwira, C. M., Carter, B. A., Yizengaw, E., Halford, A. J., Tsurutani, B. T., & Gjerloev, J. W. (2018) Geomagnetically induced currents caused by interplanetary shocks with different impact angles and speeds. *Space Weather.* 16, 636-647. DOI: 10.1029/2018SW001880

Oliveira, D. M., Hayakawa, H., Bhaskar, A., Zesta, E., & Vichare, G. (2020) A possible case of sporadic aurora observed at Rio de Janeiro. *Earth, Planets and Space.* DOI: 10.1186/s40623-020-01208-z.

RGO (1872) *Results of the Magnetical and Meteorological Observations made at The Royal Observatory, Greenwich, 1872*, London, Royal Greenwich Observatory.

Richardson, I. G., Webb, D. F., Zhang, J., *et al.*(2006). Major geomagnetic storms (Dst <= -100 nT) generated by corotating interaction regions. *Journal of Geophysical Research: Space Physics.* 111, A7, A07S09. DOI: 10.1029/2005JA011476

Riley, P., Baker, D., Liu, Y. D., Verronen, P., Singer, H., Güdel, M. (2018) Extreme Space Weather Events: From Cradle to Grave, *Space Science Reviews.* 214, 21. DOI: 10.1007/s11214-017-0456-3

Roach, F. E., Moore, J. G., Bruner, E. C., Jr., Cronin, H., Silverman, S. M. (1960) The Height of Maximum Luminosity in an Auroral Arc. *Journal of Geophysical Research.* 65, 3575-3580. DOI: 10.1029/JZ065i011p03575

Rubenson, R. (1882) *Catalogue des aurores boréales observées en Suède*, Kungliga Svenska Vetenskapsakademiens Handlingar. 18, 1-300.

Rudd, J. T., Oliveira, D. M., Bhaskar, A., Halford, A. J. (2019) How do inter-planetary shock impact angles control the size of the geoeffective magnetosphere?. *Advances in Space Research.* 63, 317–326. DOI: 10.1016/j.asr.2018.09.013.

Saiz, E., Guerrero, A., Cid, C., Palacios, J., Cerrato, Y. (2016) Searching for Carrington-like events and their signatures and triggers. *Journal of Space Weather and Space Climate.* 6, A6. DOI: 10.1051/swsc/2016001

Schlegel B., Schlegel K. (2011). *Polarlichter zwischen Wunder und Wirklichkeit*. Spektrum Akademischer Verlag. Heidelberg, DE. DOI: 10.1007/978-3-8274-2881-3

Schulz, M (1994). Direct influence of ring current on auroral oval diameter. *Journal of Geophysical Research.* 102, A7, 14149-14154. DOI: 10.1029/97JA00827

Silverman, S. M. (1992). Secular variation of the aurora for the past 500 years. *Reviews of Geophysics.* 30, 333-351. DOI: 10.1029/92RG01571

Silverman, S. M., Cliver, E. W. (2001). Low-latitude auroras: the magnetic storm of 14-15 May 1921. *Journal of Atmospheric and Solar-Terrestrial Physics.* 63, 523-535, DOI:10.1016/S1364-6826(00)00174-7

Silverman, S. M. (1995). Low latitude auroras: the storm of 25 September 1909,. *Journal of Atmospheric and Terrestrial Physics.* 57, 673 – 685. DOI:10.1016/0021-9169(94)E0012-C

Silverman, S. M. (2003), Sporadic Auroras. *Journal of Geophysical Research: Space Physics.* 108, A4, 8011, DOI:10.1029/2002JA009335

Silverman, S. M. (2006). Comparison of the aurora of September 1/2, 1859 with other great auroras. *Advances in Space Research.* 38, 136-144. DOI: 10.1016/j.asr.2005.03.157

Silverman, S. M. (2008). Low-latitude auroras: The great aurora of 4 February 1872. *Journal of Atmospheric and Solar-Terrestrial Physics.* 70, 1301-1308. DOI:10.1016/j.jastp.2008.03.012

Siscoe, G., Crooker, N. U., Clauer, C. R. (2006). Dst of the Carrington storm of 1859. *Advances in Space Research*,.38, 173-179. DOI: 10.1016/j.asr.2005.02.102

Smith, E. J., Wolfe, J. H. (1976). Observations of interaction regions and corotating shocks between one and five AU: Pioneers 10 and 11. *Geophysical Research Letters.* 3, 137-140. DOI: 10.1029/GL003i003p00137

Tromholt, S. (1902), *Catalog der in Norwegen bis Juni 1878 beobachteten Nordlichter*, Kristiana, Jacob Dybwad.

Trouvelot, E. L. (1882). *The Trouvelot Astronomical Drawing Manual* (New York: Charles Scribner's Sons).

Tsurutani, B. T., Smith, E. J., Pyle, K. R., Simpson, J. A. (1982). Energetic protons accelerated by corotating shocks: Pioneer 10 and 11 observations from 1 to 6 AU, *Journal of Geophysical Research.* 87, A9, 7389-7404. DOI: 10.1029/JA087iA09p07389

Tsurutani, B. T., Gonzalez, W. D. (1987). The cause of high-intensity long-duration continuous AE activity (HILDCAAs): Interplanetary Alfvén wave trains, *Planetary and Space Science.* 35, 4, 405-412. DOI: 10.1016/0032-0633(87)90097-3

Tsurutani, B. T., Gonzalez, W. D., Gonzalez, A. L. C., Tang, F., Arballo, J. K., Okada, M. (1995), Interplanetary origin of geomagnetic activity in the declining phase of the solar cycle. *Journal of Geophysical Research.* 100, A11, 21717-21734. DOI: 10.1029/95JA01476

Tsurutani, B. T., Zhou, X. -Y., Vasyliunas, V. M., Haerendel, G., Arballo, J. K., Lakhina, G. S. (2001). Interplanetary Shocks, Magnetopause Boundary Layers and Dayside Auroras: The Importance of a Very Small Magnetospheric Region. *Surveys in Geophysics.* 22, 2, 101-130. DOI: 10.1023/A:1012952414384

Tsurutani, B. T., Zhou, X.-Y. (2003). Interplanetary shock triggering of substorms: Wind and Polar. *Advances in Space Research.* 31, 1063-1067. DOI:10.1016/S0273-1177(02)00796-2

Tsurutani, B. T., Gonzalez, W. D., Lakhina, G. S., Alex, S. (2003). The extreme magnetic storm of 1-2 September 1859. *Journal of Geophysical Research Space Physics.* 108, A7, 1268, DOI: 10.1029/2002JA009504

Tsurutani, B. T., Gonzalez, W. D., Lakhina, G. S., Alex, S. (2005). Reply to comment by S.-I. Akasofu and Y. Kamide on "The extreme magnetic storm of 1-2 September 1859". *Journal of Geophysical Research: Space Physics.* 110, A9, A09227. DOI: 10.1029/2005JA011121

Tsurutani, B. T., *et al*. (2006a). Corotating solar wind streams and recurrent geomagnetic activity: A review. *Journal of Geophysical Research: Space Physics.* 111, A07S01. DOI: 10.1029/2005JA011273

Tsurutani, B. T., *et al*. (2006b). *Recurrent Magnetic Storms: Corotating Solar Wind Streams.* Washington DC, AGU. DOI:10.1029/GM167

Tsurutani, B. T., Lakhina, G. S., Echer, E., Hajra, R., Nayak, C., Mannucci, A. J., Meng, X. (2018) Comment on "Modeling Extreme "Carrington-Type" Space Weather Events Using Three-Dimensional Global MHD Simulations" by C. M. Ngwira, A. Pulkkinen, M. M. Kuznetsova, and A. Glocer". *Journal of Geophysical Research: Space Physics.* 123, 1388-1392. DOI: 10.1002/2017JA024779

Turner, N. E., Mitchell, E. J., Knipp, D. J., Emery, B. A. (2006). Energetics of Magnetic Storms Driven by Corotating Interaction Regions: A Study of Geoeffectiveness, Recurrent Magnetic Storms: Corotating Solar Wind Streams. Geophysical Monograph 167. (Eds. B. Tsurutani, R. McPherron, W. Gonzalez, G. Lu, J. H. A. Sobral, and N.

Gopalswamy). ISBN-13: 978-0-87590-432-0. Published by the AGU Books Board, AGU, Washington, DC USA, 2006, p.113. DOI: 10.1029/167GM11

Twining, A. C. (1872). Aurora of Feb. 4th, 1872. *American Journal of Science and Arts.* 3, 274-281. DOI:10.2475/ajs.s3-3.16.273

Usoskin, I. G., Kromer, B., Ludlow, F., Beer, J., Friedrich, M., Kovaltsov, G. A., Solanki, S. K., Wacker, L. (2013). *Astronomy & Astrophysics.* 552, L3. DOI: 10.1051/0004-6361/201321080

Usoskin, I. G., *et al*. (2015). The Maunder minimum (1645-1715) was indeed a grand minimum: A reassessment of multiple datasets. *Astronomy & Astrophysics.* 581, A95. DOI: 10.1051/0004-6361/201526652

Vallance Jones, A. (1992). Historical review of great auroras. *Can. J. Phys.*, 70, 479 – 487, DOI: 10.1139/p92-083

Vaquero, J. M., Trigo, R. M., Gallego, M. C.: 2007. Sporadic aurora from Spain. *Earth, Planets and Space.* 59, e49-e51, DOI:10.1186/BF03352061

Vaquero, J. M., Gallego, M. C., Barriendos, M., Rama, E., Sanchez-Lorenzo, A. (2010). Francisco Salvá's auroral observations from Barcelona during 1780-1825. *Advances in Space Research.* 45, 1388-1392. DOI: 10.1016/j.asr.2010.02.009

Vauqero, J. M., Gallego, M.-C., Dominguez-Castro, F. (2013). A possible case of Sporadic Aurora in 1843 from Mexico. *Geofísica Internacional.* 52, 87-92. DOI:10.1016/S0016-7169(13)71464-8

Vázquez, M., Vaquero, J. M., Gallego, M. C., Roca Cortés, T., Pallé, P. L. (2016). Long-Term Trends and Gleissberg Cycles in Aurora Borealis Records (1600 – 2015). *Solar Physics.* 291, 613-642. DOI: 10.1007/s11207-016-0849-6

Viljanen, A., Myllys, M., Nevanlinna, H.: 2014, Russian geomagnetic recordings in 1850-1862 compared to modern observations. *J. Space Weather Space Clim.* 4, A11, DOI: 10.10.1051/swsc/2014008

Willis, D. M., Stephenson, F. R. (2001). Solar and auroral evidence for an intense recurrent geomagnetic storm during December in AD 1128. *Annales Geophysicae.* 19, 289-302. DOI: 10.5194/angeo-19-289-2001

Willis, D. M., Stephenson, F. R., Fang, H.(2007). Sporadic aurorae observed in East Asia. *Annales Geophysicae.* 25, 417-436. DOI:10.5194/angeo-25-417-2007

Willis, D. M., Davis, C. J.: 2014. Evidence for recurrent auroral activity in the twelfth and seventeenth centuries, in: W. Orchiston *et al*. (eds.) *New Insights From Recent Studies in Historical Astronomy: Following in the Footsteps of F. Richard Stephenson.* Springer, Cham.

Yokoyama, N., Kamide, Y., Miyaoka, H. (1998). The size of the auroral belt during magnetic storms. *Annales Geophysicae.* 16, 566-573. DOI: 10.1007/s00585-998-0566-z

Yue, C., *et al*. (2010). Geomagnetic activity triggered by interplanetary shocks. *Journal of Geophysical Research: Space Physics.* 115, A5, DOI: 10.1029/2010JA015356

Zhou, X., Tsurutani, B. T. (1999). Rapid intensification and propagation of the dayside aurora: Large scale interplanetary pressure pulses (fast shocks). *Geophysical Research Letters.* 26, 8, 1097-1100. DOI: 10.1029/1999GL900173

Zhou, X., Tsurutani, B. T. (2001). Interplanetary shock triggering of nightside geomagnetic activity: Substorms, pseudobreakups, and quiescent events. *Journal of Geophysical Research.* 106, A9, 18957-18968. DOI: 10.1029/2000JA003028