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Key Points:
- The earliest known example of prolonged aurora sightings in Japan was documented on 21–23 February 1204
- Majority of the prolonged aurora activity events in China (900–1200) occurred around solar maxima rather than solar minima
- The prolonged aurora activity events did not occur during the Oort Minimum (1010–1050)

Supporting Information:
- Supporting Information S1

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Historical space weather monitoring of prolonged aurora activities in Japan and in China

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Abstract Great magnetic storms are recorded as aurora sightings in historical documents. The earliest known example of "prolonged" aurora sightings, with aurora persistent for two or more nights within a 7 day interval at low latitudes, in Japan was documented on 21–23 February 1204 in *Meigetsuki*, when a big sunspot was also recorded in China. We have searched for prolonged events over the 600 year interval since 620 in Japan based on the catalogue of *Kanda* [1933] and over the 700 year interval since 581 in China based on the catalogues of Tamazawa et al. (2017) and Hayakawa et al. (2015). Before the Meigetsuki event, a significant fraction of the 200 possible aurora sightings in *Sòng* dynasty (960–1279) of China was detected at least twice within a 7 day interval and sometimes recurred with approximately the solar rotation period of 27 days. The majority of prolonged aurora activity events occurred around the maximum phase of solar cycles rather than around the minimum, as estimated from the ^{14}C analysis of tree rings. They were not reported during the Oort Minimum (1010–1050). We hypothesize that the prolonged aurora sightings are associated with great magnetic storms resulting from multiple coronal mass ejections from the same active region. The historical documents therefore provide useful information to support estimation of great magnetic storm frequency, which are often associated with power outages and other societal concerns.

1. Introduction

Aurora sightings have been recorded in historical documents of low-latitude Japan and southern China because the aurora presents unusual and impressive appearances of the night sky. The occurrence of aurora in low-latitude regions is a manifestation of the great magnetic storms. Note that in accordance with *Tsurutani et al.* [1992] we use "great storm" to mean *Dst* more negative than −250 nT, when such data are available. The physics of low-latitude aurora during major storms, and their persistence over a few days, have been recently discussed by *Lockwood and Barnard* [2015], based on the expanding-contracting polar cap paradigm associated with the solar open flux [*Lockwood et al.*, 2009]. In present day, great storms can induce power grid outages, damage spacecraft, and hamper human activities in space [*Tsurutani et al.*, 1992; *Lanzerotti*, 1992]. It is therefore important to study the detailed low-latitude auroral descriptions in historical documents to understand the occurrence pattern of great storms. Further, knowing the equatorward boundaries of great storm auroral ovals may help to mitigate such potential space hazards [*Kataoka*, 2013; *Kataoka and Ngwira*, 2016].

Low-latitude auroras seen in more recent times have been interpreted as having two causes: one is stable auroral red arc [*Rees and Roble*, 1975; *Zhang*, 1985] and another is precipitation of electrons with broadband energy [*Shiokawa et al.*, 2005]. Because the appearances of low-latitude aurora as described in the historical documents discussed here have a variety of colors, shapes, and motions [*Nakazawa et al.*, 2004; *Hayakawa et al.*, 2015], there is a possibility that the historical documents record instances of great storm aurora similar to those observed during the 1859 Carrington storm [*Green and Boardsen*, 2006; *Hayakawa et al.*, 2016b].

Complex and large sunspots are sometimes eruptive enough to launch multiple coronal mass ejections in a few days, which can be the most geo-effective pattern to create the great magnetic storms [*Baker et al.*, 2013; *Ngwira et al.*, 2013; *Liu et al.*, 2014; *Kataoka et al.*, 2015; *Shiota and Kataoka*, 2016]. *Lockwood et al.* [2016]

have recently shown that larger storms are caused by coronal mass ejections that generate more persistent southward interplanetary magnetic field. Further, multiple magnetic storms sometimes occur within several days, and the major driver of such multiple storms is also a series of coronal mass ejections [*Kataoka and Miyoshi*, 2006]. Here we note two different aspects on the multiple occurrences of coronal mass ejections. First, a series of coronal mass ejections in a few days tend to enhance their geo-effectivity due to their interactions in the interplanetary space to cause the great magnetic storms. Second, it is natural for flare-productive sunspots to launch multiple coronal mass ejections, with the high activity tending to continue for several days and subsequently in the next solar rotation. In fact, there was a preceding large magnetic storm on 28–29 August 1859 with several aurora sightings at 20–40° magnetic latitude, 4–5 days before the well-known Carrington storms on 2–3 September 1859 [*Kimball*, 1960; *Green and Boardsen*, 2006; *Hayakawa et al*., 2016b], which was the largest event for the last 200 years. It is therefore important to investigate reports of multiple occurrences of low-latitude aurora sightings within a period of several days or even in the successive solar rotations to assess if these reports may be indicators of great storms.

There are, however, uncertainties and limitations in the data obtained from historical documents, and very careful inspections are always needed. We therefore have conducted a new project since 2015, "Aurora 4-D Project," to carefully and thoroughly investigate the historical documents, collaborating with researchers of historical literature. During the interaction and discussion of the team meetings in 2015, we noticed that one relatively robust and important piece of information to be obtained from the historical documents would be a clustering pattern of multiple aurora sightings in short time. For example, one of the well-known events on 17 September 1770, in which more than 40 sightings were reported overall Japan [*Willis et al*., 1996; *Nakazawa et al*., 2004], had also a following aurora sighting on 18 September 1770 as written in Japanese "*Zoku Shi Gu Shou*" or in Chinese historical documents [*Kawamura et al*., 2016], positively supporting the current understanding of the importance of a series of coronal mass ejections to cause extreme storms. The purpose of this paper is to describe the historical examples of such prolonged aurora sightings from Japanese historical documents in detail and to find the occurrence pattern of much earlier possible prolonged aurora events based on the list of aurora candidates in Chinese official histories made by some of the authors [*Hayakawa et al*., 2015; *Tamazawa et al*., 2017]. There have been a number of attempts to reconstruct the detailed solar cycles before the age of sunspot observations [e.g., *Schove*, 1955]. We also try in this paper to compare the occurrence of prolonged aurora sightings with solar cycle phase using our own detailed analysis of tree rings. *Vazquez et al*. [2014] studied the long-term spatial and temporal variations of aurora borealis events in the period 1700–1905. More recently, *Usoskin et al*. [2015] used multiple data sets to review the auroral activity during the Maunder Minimum period 1645–1715. We extend the efforts to investigate aurora in the interval 581–1279.

2. Earliest Known Examples of Prolonged Aurora Activities in Japanese Historical Documents

The earliest known example of prolonged magnetic storms in Japan, based on the catalogue of *Kanda* [1933], is the aurora sightings on 21 and 23 February 1204 as documented in *Meigetsuki* by *Fujiwara-no-Sadaie*, the famous Japanese poet who lived in Kyoto (see Figures 1 and 2). Meigetsuki is a diary written by Sadaie for a time period from 1180 to 1235, with some part lost by present days. The diary has recently been highly evaluated as a scientifically important document especially in astrophysics. We consulted his handwritten manuscript in *Shigure Tei* (*Fujiwara-no-Sadaie, 1993, Meigetsuki, Tokyo, facsimile edition*).

He wrote as follows (English translation is shown in italic):

> *On 1204/02/21, it was sunny. … After sunset, red vapor appeared in the direction of north and north-east. The lower part of red vapor was shaped like a rising moon and colored white and bright. Its stripes extended faraway and was like smokes in fires. There were four or five of white parts and three or four of red vapors appeared. Is it neither cloud nor stands within clouds? Its light did not get darken and red light is mixed in the white light. It is nothing but a mystery. It is also very dreadful. On 1204/02/23, it was sunny and quite windy. … In the time when to put a fire on the lamp, red vapor appeared in the north and north-east. It was like a distant mountain burning. It was very dreadful.*

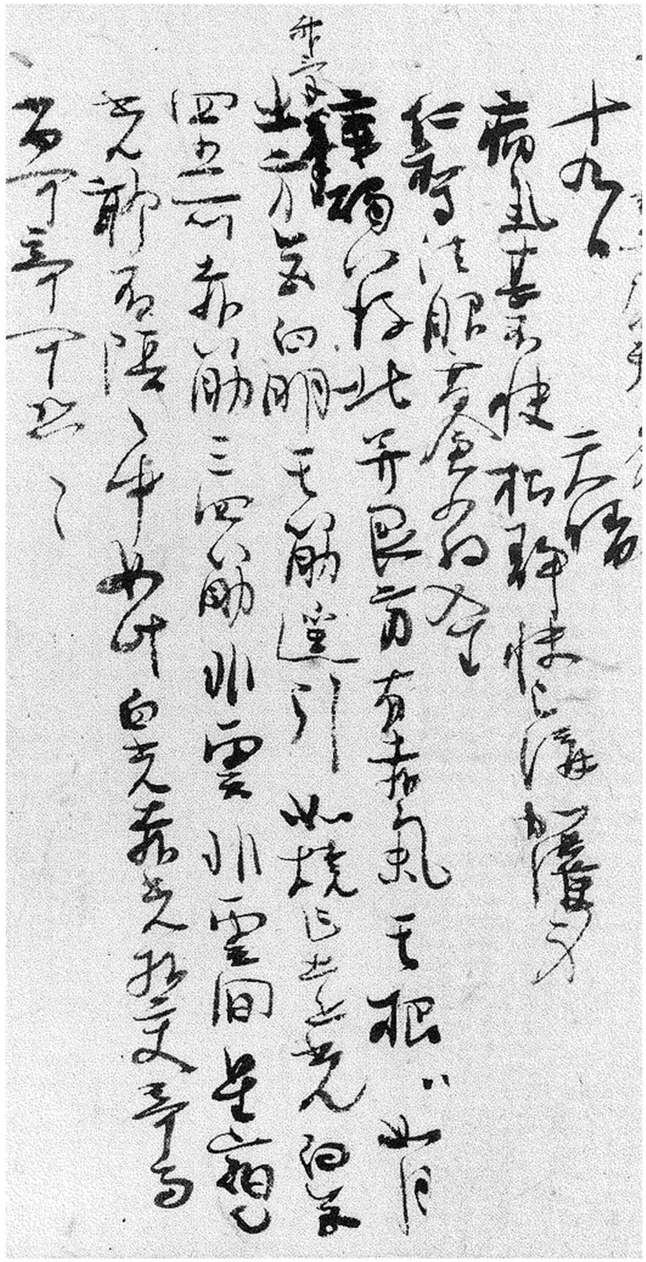

Figure 1. An aurora-like record on 21 February 1204 in Meigetsuki, p511–512.

The actual aurora sightings in Kyoto, documented in Meigetsuki, are supported by a separate historical document. *Omuro Soshoki*, a historical document and national treasure written by unidentified person, describes an observation of red vapor 3 days straight, within its endorsement to complement the main text, as follows (*Omuro Soshoki, p118, Nara National Research Institute for Cultural Properties (1964), Historical Records of Nin'na Temple*):

> *On 1204/02/21, at 20:00, red vapor appeared with white cloud mixed and was seen from north-west to north-east. On 1204/02/22 as well. On 1204/02/23, as well. Takashige stated that these were very rare disaster. We put off the pilgrimage to Koyasan.*

Koyasan is located a few days walking distance to the south from Kyoto. The postponement (and probably suspension) of the pilgrimage was likely an attempt to avoid being involved in any further disaster that

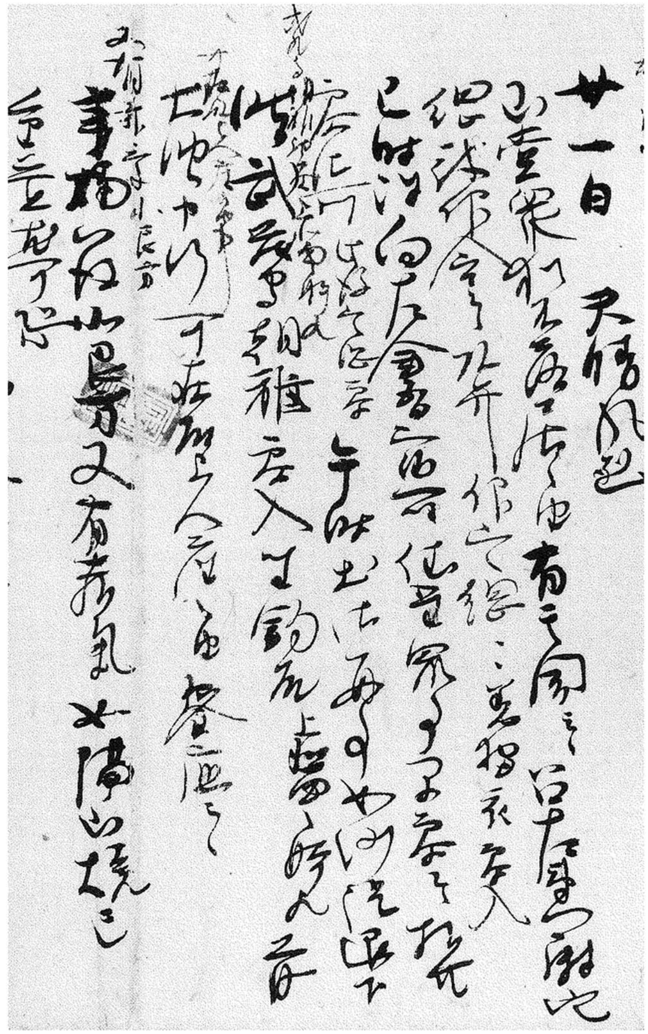

Figure 2. Aurora-like records on 21 and 23 February 1204 in Meigetsuki, p512.

could develop associated with the ominous “red vapor,” which itself is an important material of Japanese history to understand the response of people to natural calamity at that time. Since the weather was fine in Kyoto as written in Meigetsuki, the absence of the aurora sighting on 22 February in Meigetsuki may imply a relatively weak magnetic storm and relatively faint appearance on 22 February comparing with those on 21 and 23 February.

These reports for red vapor on 21, 22, and 23 February 1204 can also be supported by records of solar activity in other countries as well. At least there is a record of naked-eye sunspot in China on the same date with Sadaie’s first auroral observation (supporting information Text S1). In the following month, another aurora sighting on 30 March was also recorded in Meigetsuki, and there are two more reports from China (*Sòngshǐ*, Five Elements IIb: p1413; Sòngshǐ, Astronomy XIII: p1316) and one from France (*Bouquet M, 1738, Recuil des historiens des Gaules et de la France, Paris, XVIII, 268*). These records can be interpreted as examples of the recurrent events associated with the next solar rotation.

Additionally, we present an event that is prior to this auroral event based on the catalogues by *Tamazawa et al*. [2017] and *Hayakawa et al*. [2015] that cover A.D. 581–959 and A.D. 960–1279. It is possibly the earliest documented example of a prolonged auroral sighting in China ((*Jiùwǔdàishǐ, Jìnshū, Gāozǔ: p. 994,* event C01 in supporting information Text S2). This example shows an interesting complex nature of aurora appearance. The English translation is shown as follows:

Table 1. Prolonged Aurora Sightings

#	Year/Month/Day	Interval (Days)	Moon Phase[a]
C01	937/2/14	1	0.03, 0.06
C02	1003/7/14	5	0.42, 0.59
C03	1007/4/12	1	0.75, 0.79
C04	1065/5/24	1	0.57, 0.60
C05	1074/7/16	1, 5, 1	0.67, 0.70, 0.87, 0.90
C06	1079/5/13	3	0.34, 0.45
C07	1088/8/12	1	0.78, 0.81
C08	1127/9/20	2, 5	0.42, 0.49, 0.65
C09	1137/2/14	6	0.76, 0.96
C10	1160/12/18	1	0.65, 0.68
C11	1161/12/21	1	0.12, 0.15
C12	1165/5/30	4, 3	0.65, 0.77, 0.91
C13	1170/12/3	7	0.81, 0.05
C14	1171/11/3	1	0.13, 0.16
C15	1176/9/29	1	0.82, 0.85
C16	1187/12/17	1	0.54, 0.57
C17	1193/12/5	1	0.35, 0.38
C18	1194/7/2	7	0.44, 0.68

[a]Moon phase was calculated by the same method shown in *Kawamura et al*. [2016] to check that the prolonged aurora sightings can be found in random moon phases including new moon = 0.0 and full moon = 0.5.

On 14 Feb. 937, at night, red and white vapors appeared alternately, like a cultivated and exploited bamboo forest, from 23:00 to 3:00, muddily from north to the middle in the sky, flickering unstably went around the 28 lunar mansions and disappeared at the dawn.

The flickering or pulsating aurora may imply that very strong auroral activities can occur even in the low-latitude regions such as magnetic latitude of 35° during extreme magnetic storms, as reported by *Green and Boardsen* [2006] for the Carrington storm. Such a different appearance in addition to the existence of typical white rays, etc. also suggests the relative magnitude of this great magnetic storm, based on our current knowledge of stable auroral red arcs, broadband electrons, etc. This passage above suggests that our ancestors recorded a great auroral storm in the Northern Hemisphere winter of the year 937, motivating us to investigate and to describe the frequency of such events and to bridge this information to modern day knowledge of great storms.

3. Occurrence Pattern of Prolonged Aurora Activities in Chinese Historical Documents

We investigated the occurrence pattern of prolonged aurora sightings from the 700 year database (http://www.kwasan.kyoto-u.ac.jp/~palaeo) of historical auroras by *Tamazawa et al*. [2017] and *Hayakawa et al*. [2015]. Their terms in oriental historical documents are known as colored "vapor," "cloud," "light," etc. The most famous one is red vapor as seen in extreme magnetic storms such as Carrington event [*Kanda*, 1933; *Keimatsu*, 1970; *Yau et al*., 1995; *Hayakawa et al*., 2015, 2016a, 2016b]. We have ~60 of historical aurora candidates within the period during A.D. 581–959 [*Tamazawa et al*., 2017] and ~200 of them within the period 960–1279 [*Hayakawa et al*., 2015], which are somewhat similar with the frequency of low-latitude aurora during the recent observational period (roughly once a year) [*Shiokawa et al*., 2005].

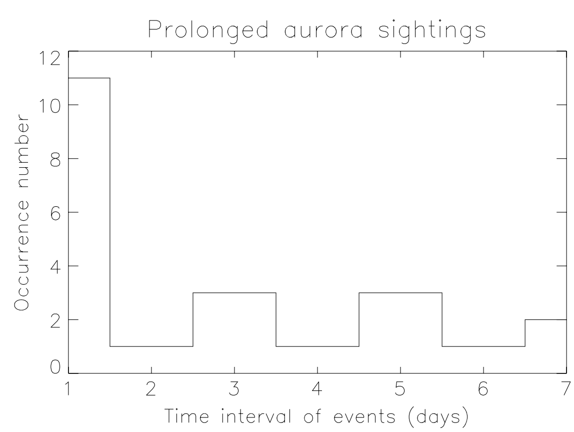

Figure 3. Occurrence number distribution of the time interval (days) between aurora sightings found in China for 300 years (900–1200), as also shown in Table 1 and in supporting information Text S5.

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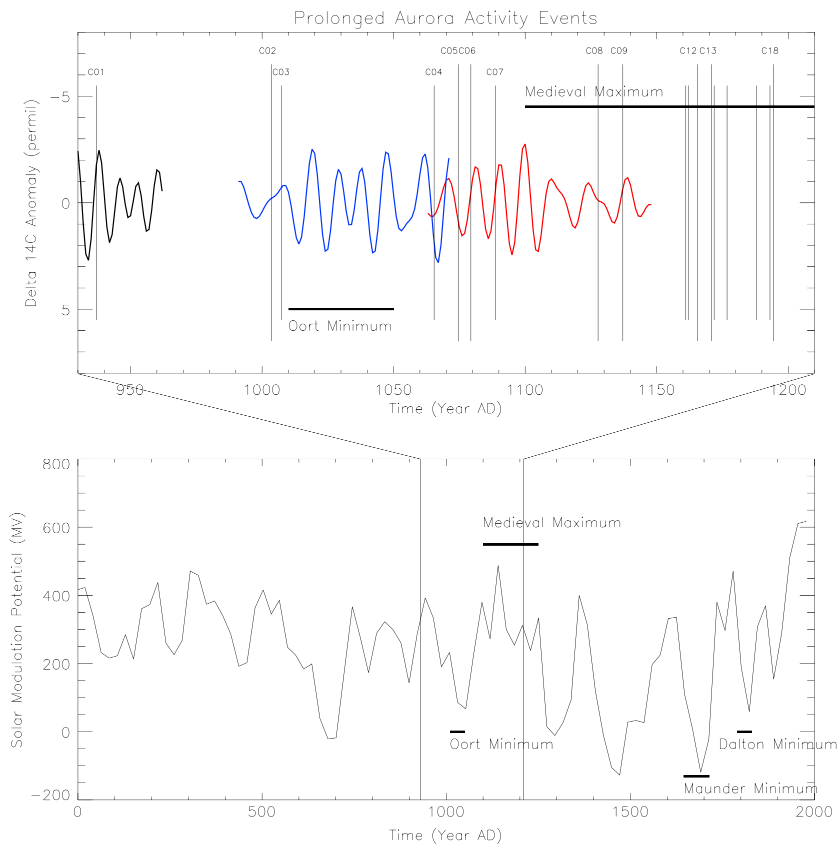

Figure 4. Comparison between the prolonged aurora activity events in China (vertical lines) and solar cycles. Solid curves present the band-pass filtered delta ^{14}C to approximately show the 11 year solar cycles, where negative anomaly peaks correspond to the solar maxima with the ambiguity of approximately 2 years. Short vertical lines show the multiple aurora sightings within 3 days, while long vertical lines show the events within 7 days. (top) The data for (blue curve) the Oort Minimum and for (red curve) Medieval Maximum were obtained from *Menjo et al.* [2005] and *Damon et al.* [1998], respectively. The data before 970 (black curve) were obtained from *Miyahara et al.* [2008]. (bottom) The several grand minima in the solar modulation potential for the last 2000 years as reconstructed from the tree ring/ice core analysis by *Steinhilber et al.* [2012].

To seek the occurrence pattern, we searched 2 week intervals, which approximately correspond to the time frame from the appearance of large sunspots from the eastern limb of the Sun to the disappearance at the western limb. We further searched within the 2 week intervals for instances of at least two auroral sightings within 7 days. When such instances were identified, a detailed visual inspection of the records was conducted to eliminate meteorological phenomena, such as sundog-like events. Note that an aurora that persisted over midnight is not recorded as being on two different days in this paper. The final prolonged aurora activity events are shown in supporting information Text S2 with our English translation. Based on the current understanding of space weather [e.g., *Kataoka and Miyoshi*, 2006], it is natural to assume that coronal mass ejections from the same active region can cause multiple magnetic storms for the time interval up to 7 days, especially across the meridian center of the Sun. *Oler* [2004] reported such behavior for the late October 2003 storms.

The complete list of the possible dates of the prolonged aurora activities is shown in Table 1 with further descriptions in supporting information Text S2. Figure 3 summarizes the occurrence distribution of the time interval (days) between the aurora sightings. From the analysis of the continuous record, it is also found that aurora sightings showed a clustering occurrence in time. For example, out of approximately 200 possible aurora sighting events, 24 events (12 event pairs) occur multiple times within 3 days, and an additional 15 events occur multiple times in 7 days. The weak enhancement in odd days would be an artificial product due to small number of events lasting for more than 2 days. There are 35 recurrent events within approximately a subsequent solar rotation period. Four of the prolonged aurora activity events (C02, C05, C09, and C12) have recurrent aurora sighting events. Figure 4 shows the comparison of the annually measured tree-ring ^{14}C data with

Table 2. List of the Great Magnetic Storms of *Dst* < −250 nT During Solar Cycle 22 (1986–1996)

#	Year/Month/Day/Hour	*Dst* (nT)	Note
G01	1986/2/9/1	−307	
G02	1989/3/14/2	−589	
G03	1989/9/19/5	−255	a
G04	1989/10/21/17	−268	a
G05	1990/4/10/19	−281	
G06	1991/3/25/1	−298	
G07	1991/10/29/8	−254	
G08	1991/11/9/2	−354	
G09	1992/5/10/15	−288	

[a]G04 is the recurrent of G03.

the occurrence of prolonged aurora activities up to 7 days. The number of events correspond to the event list shown in supporting information Text S2.

The ^{14}C data for the Oort Minimum and Medieval Maximum were obtained from *Menjo et al*. [2005] and *Damon et al*. [1998], respectively. Several other grand minima are also shown in Figure 4 (bottom), using the reconstruction data from *Steinhilber et al*. [2012], where the solar modulation potential refers to the solar magnetic activity to shield galactic cosmic rays. The data for Oort Minimum (blue curve) and for Medieval Maximum (red curve) were obtained from *Menjo et al*. [2005] and *Damon et al*. [1998], respectively. The ^{14}C data before 970 (black curve) were obtained from *Miyahara et al*. [2008]. The approximately 2 year time lag between the production of ^{14}C and its absorption into trees, due to the carbon cycle [*Siegenthaler et al*., 1980], is taken into account. The Fourier transform band-pass filter of 8–15 years was used for 990–1150 data shown in Figure 4. A band-pass filter of 7–11 years was applied for the data before 960 based on the wavelet transform that suggested that the mean length of solar cycles was about 9 years (±1 year) at that time [*Miyahara et al*., 2008]. Although ^{14}C variations may be affected by the changes of carbon cycle (e.g., exchange rate of ^{14}C between atmosphere and ocean), such an effect is negligible during the Holocene [*Usoskin*, 2013]. We also note that although decadal variation of ^{14}C is strongly attenuated in the carbon cycle, the above method of band-pass filtering applied to the annually measured ^{14}C data for the modern period [*Stuiver et al*., 1998] successfully detects decadal solar cycles and reproduces the timing of solar cycle minima for solar cycle 1 to 18 with an uncertainty of ±1.7 years. The obtained solar cycle phase in this study therefore has an uncertainty of approximately 2 years which can also be seen in the discrepancy in the red and blue curves around A.D. 1070. There is also similar ambiguity on the phase of the black curve.

It is found that the occurrence pattern of prolonged aurora activities has two major features. One is the absence of events during the Oort Minimum when the solar activity is weaker than average for a long time from 1010 to 1050. Another is a solar cycle dependence that the majority of events occurred around (within 2 years uncertainty of) the solar maximum (C01, C03, C06, C07, and C09) rather than around the solar minimum (C04 and C05). The solar cycle phases of the other two events (C02 and C08) are unclear from our analysis. This tendency is consistent with the modern understanding that a series of coronal mass ejections cause the great magnetic storms, which result in the prolonged aurora activities for several days. It would therefore be reasonable to hypothesize that the prolonged aurora sighting events resemble the recent "Halloween

Table 3. List of the Great Magnetic Storms of *Dst* < −250 nT During Solar Cycle 23 (1996–2009)

#	Year/Month/Day/Hour	*Dst* (nT)	Note
G10	2000/4/7/1	−288	
G11	2000/7/16/1	−301	
G12	2001/3/31/9	−387	a
G13	2001/3/31/22	−284	a
G14	2001/4/11/24	−271	
G15	2001/11/6/7	−292	
G16	2003/10/30/1	−353	b
G17	2003/10/30/23	−383	b,c
G18	2003/11/20/21	−422	c
G19	2004/11/8/7	−374	d
G20	2004/11/10/11	−263	d

[a]G13 and G12 are multiple events.
[b]G16 and G17 are multiple events.
[c]G18 is the recurrent of G17.
[d]G19 and G20 are multiple events.

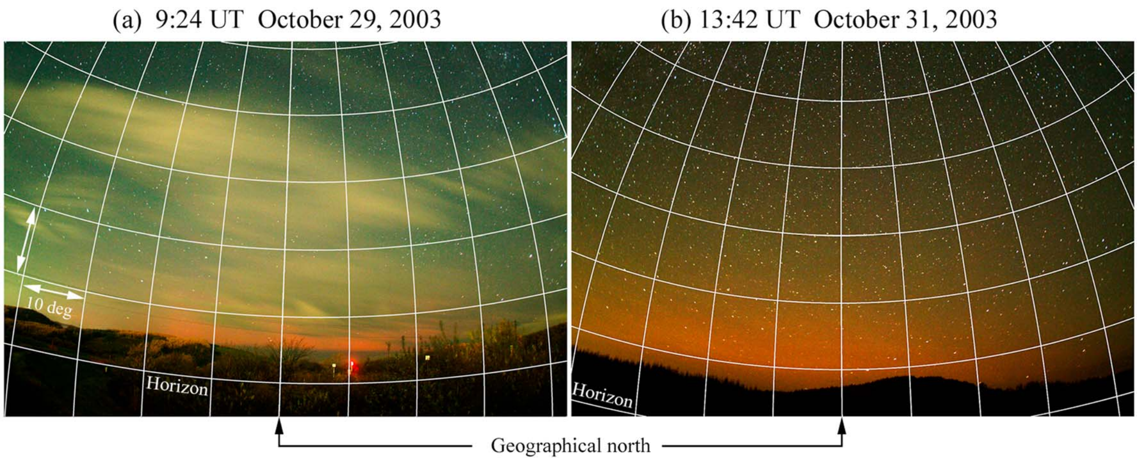

Figure 5. Examples of the color image of auroras captured on (a) 29 October 2003 and on (b) 31 October 2003 in Nayoro city (142.5, 44.4), Hokkaido, Japan. Grid lines show the elevation and azimuthal angles with an interval of 10°.

storm"-like great magnetic storms which were caused by multiple eruptive events from large sunspots [*Oler*, 2004].

4. Discussion

In this section, we interpret our results in light of the data presented above and merge these with our understanding of the temporal variation of Earth's magnetic field. Finally, we address the implications of our work.

4.1. Comparison With Modern Great Magnetic Storms

We propose the hypothesis that the prolonged aurora activities are a natural consequence of eruptive sunspots, i.e., multiple eruptions from the flare-productive sunspots in 7 days. A series of multiple coronal mass ejections from a single solar active region often originate from so-called homologous flares, a series of repetitive flares that occur at the same place in the active region with similar morphology [e.g., *Zhang and Wang*, 2002; *Takasaki et al*., 2004; *Chandra et al*., 2011]. In fact, all of the greatest storms in solar cycles 22 (1986–1996) and 23 (1996–2009) as shown in Tables 2 and 3 are associated with flare-productive sunspots. Further, a subclass of recurrent storms, not driven by corotating interaction regions but rather driven by "recurrent" coronal mass ejections in approximately 27 days, have been confirmed in recent data set [*Crooker and McAlister*, 1997]. We do not consider a coronal hole as an important factor in this study because the magnetic field strength of the solar wind originated from coronal hole is typically too weak to cause great magnetic storms, rarely reaching the *Dst* peak < -150 nT [*Richardson et al*., 2006].

There are several examples of aurora sightings in Japan during the recent great storms. For example, *Miyaoka et al*. [1990] reported aurora sightings and the color image of red aurora as seen from Hokkaido, Japan, during the magnetic storm of G04. More recently, other color images of auroras captured by a color digital camera in Hokkaido, Japan, were also reported during some of above events (G12, G17, and G19) [*Suzuki et al*., 2015]. Figure 5 shows the examples of the color images of auroras captured on 29 and 31 October 2003 in Nayoro city (44.4°N, 142.5°E, geographic coordinate system), Hokkaido, Japan. Red and diffusive features in the low elevation angle are evident in both images.

It is worthwhile to compare the obtained results with modern observations to quantitatively learn further possible meanings from historical documents. Tables 2 and 3 show the recent great magnetic storms with the *Dst* index of < -250 nT in solar cycles 22 and 23, respectively. As a modern definition of "multiple events" in the column of Tables 2 and 3, we include the multiple storms separated by at least 12 h (G12–G13 and G17–G18), although they cannot be essentially discriminated as prolonged events in historical documents. It is found that all of the great storms except for the G01 event occur around the solar maximum or in the declining phase, which is consistent with the occurrence of prolonged aurora activities in medieval China.

The occurrence pattern of the great magnetic storms in solar cycles 22 and 23 shows a total of six events (G12, G13, G16, G17, G19, and G20) out of 20 great storms that occur multiple times within a week. We do

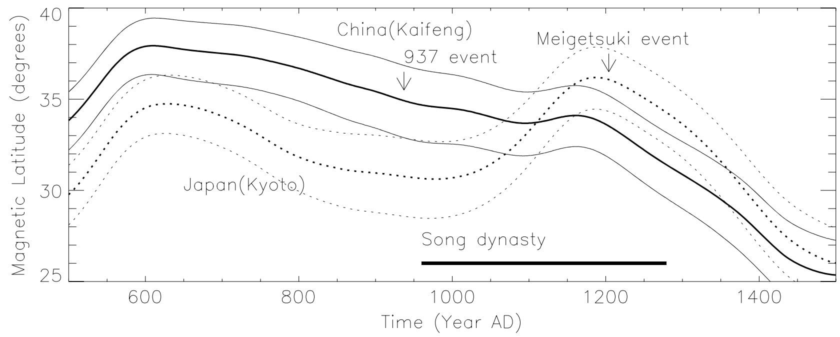

Figure 6. Time evolution of magnetic latitudes at Kāifēng (China) and at Kyoto (Japan) as shown by thick solid and thick dotted curves, respectively. The error bars of one standard deviation, as indicated by thin curves, are evaluated by the bootstrap method [*Korte and Constable*, 2011].

not yet have any great storms in solar cycle 24 (2009 to present). Four of the great magnetic storms (G03–G04 and G17–G18) recurred in 27 days. Note that the Halloween storms in October 2003 fulfill both the multiple occurrence and 27 day recurrence, which reminds us of the Meigetsuki event in 1204. The somewhat high occurrence frequency of multiple storm events for the recent solar cycles 22–24 against the prolonged aurora activity events is not inconsistent, considering the slightly different criteria between the multiple storm events and prolonged aurora activity events.

It is important to note that the magnitudes of multiple storms themselves are especially large (e.g., G16 and G17; G19 and G20), and they tend to occur during the declining phase of solar cycle 23 [*Kataoka and Miyoshi*, 2006]. *Tsurutani et al*. [1992] presented the great storms of solar cycle 21 and found that one great storm occurred in the solar minimum. *Knipp et al*. [2016] discussed a great storm from solar cycle 20 that occurred in the early rising phase of solar cycle 20. That storm had multiple coronal mass ejections, at least two of which combined to create the great storm with the peak *Dst* index of −387 nT. *Kilpua et al*. [2015] showed that the great magnetic storms occur rather randomly, not clearly depending on the solar cycles, based on the longer-term data obtained since 1868. Combining the above results, we expect that relatively isolated great storm, which continues only 1 day without causing prolonged aurora activities in low latitudes for several days, may occur rather randomly. As a future work, it would be interesting to test the hypothesis raised in this study by further investigating the solar cycle phase dependence of the occurrence of prolonged aurora activity events by measuring the delta ^{14}C record especially after 1150 with annual resolution. It would also be possible to increase the number of both isolated and prolonged events, combining the historical documents from many other countries over the world in very great detail, as historical documents let us trace auroral records back up to A.D. 771/772 with drawings [*Hayakawa et al*., 2017] and up to B.C. 567 with literal records [*Stephenson et al*., 2004; *Hayakawa et al*., 2016c].

4.2. Historical Geomagnetic Field

The occurrence frequency of aurora sightings always depends on the actual magnetic latitude at that time because the higher magnetic latitude, the greater chance of aurora sightings [*Vazquez et al*., 2014; *Lockwood and Barnard*, 2015]. The geographic coordinates of *Kāifēng* (China) and Kyoto (Japan) are (34.8°N, 114.4°E) and (35.0°N, 135.8°E), respectively. We computed the temporal evolution of the magnetic latitude for each location for the time interval from 500 to 1500. In this paper we define the magnetic latitude by a standard dipole field expression of $\tan^{-1}(0.5 \tan I)$, where the magnetic inclination I is obtained from the global geomagnetic field model CALS3k.4b [*Korte and Constable*, 2011]. It is worthwhile to note here that the Meigetsuki event occurred around the peak time of the magnetic latitude of Kyoto, Japan, for the last 1500 years (Figure 6). That would be one of the major reasons why this event was the earliest known example of prolonged aurora activities in Japan. It is also notable that the magnetic latitude of Kāifēng, China, was relatively stable and gradually decreased for the time period from 900 to 1200, actually within the error bars, and then monotonically and rapidly decreased after 1200. The continuous record during the *Sòng* dynasty therefore provides a relatively robust data to investigate the occurrence rate without significant correction of magnetic latitude.

4.3. Further Implications

As an implication, the occurrence pattern of prolonged aurora activity events also tells us additional important information on what is the most geo-effective solar activity. Multiple occurrences of coronal mass ejections have been known as a preferred condition for large flux of solar energetic particles [*Gopalswamy et al.*, 2004]. Past solar energetic particles are sometimes detected by nitrate in tree rings or possibly also by cosmogenic nuclides in ice cores and tree rings, although the origin of such peaks is not fully understood especially for nitrate [*Wolff et al.*, 2012]. Some examples of nitrate spikes in ice cores are associated with other deposited isotopes and compounds which indicate other origins (e.g., forest fires) and not solar energetic particles. Also, close inspection reveals that the dates are not in good agreement with magnetic storms. Since such proxy data are obtained only with yearly resolution in most cases, they may be of a cumulative signal of several events. If multiple solar energetic particle events turned out to have been occurred, then it can significantly change the estimation of the magnitude of each event by several times smaller, compared to the case of assuming a single flare. Investigating the successive occurrences of coronal mass ejections would therefore be essential and contributes to understanding such proxy data as well. Understanding of the recurrent coronal mass ejections as well as solar energetic particles can also impact on constructing the basis of "all-clear" alert for astronauts, which notify them very low probability of solar energetic particle events in near future, for avoiding any significant human radiation dose in space [*Reames*, 1999].

5. Conclusions

Recent studies have concentrated on the relationship of aurorae and sunspot over the past three or four centuries, while our study goes far back in time to A.D. 900. Historical documents tell us that a significant fraction of the great magnetic storms shows a clustering occurrence in time, multiple aurora sightings in a few days and sometimes recurred next month, like the 2003 Halloween storms. The earliest known example of such prolonged aurora sightings in Japan is found on 21–23 February 1204, with a Chinese record of big sunspot on the same date, when the magnetic latitude of Kyoto was the highest for the last 2000 years. The possible earliest prolonged aurora sighting in China is also found in 937, which shows a variety of morphological types even in the low-latitude aurora, which reminds us of the similarity with the 1859 Carrington storm. We hypothesize that those prolonged aurora sightings are such great magnetic storms as a result of multiple coronal mass ejections from the same active region. Comparison with the delta ^{14}C data from tree rings revealed that the prolonged great magnetic storms do not occur during the grand minimum. The majority of prolonged events occurred around the solar maximum rather than around the solar minimum, which is important and useful knowledge to prepare and to mitigate the space weather hazards in the future.

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