Aurora Sightings Observed in Chinese History Caused by CIRs or Great-storm CMEs

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Abstract

Auroras observed at middle and low geographic latitudes are related to external inputs and varying geomagnetic fields. This work aims to exclude corotating interaction region (CIR) storms and identify strong coronal mass ejection (CME) storms according to historical auroral records when the geomagnetic field varies substantially. An existing catalog of the aurora records in Chinese history reported by Zeng & Jin from 193 B.C. to 1911 A.D. is used. Archaeomagnetic field models are adopted to estimate the variation of the dipole field. According to the empirical relation between the equatorward boundary of the auroral oval, Dst index, and geomagnetic field intensity, the auroras caused by CIRs can be excluded, and those caused by strong CMEs are identified. After 1500 A.D., China’s magnetic latitude decreased substantially due to the pole shift. This shift provides a better opportunity to investigate the existence of great-level storms. These great-storm CMEs occurred in both solar maximum and minimum. The space weather modeling framework is used to calculate the cusp area and the downward ion flux through the cusp for varied geomagnetic field and solar wind. For the present solar wind condition and tilt angle <15°, stronger geomagnetic field tends to generate a larger cusp area and higher ion flux through the cusp. For the weaker solar wind in the Maunder minimum, the ion flux is lower, but the cusp area is similar to that at present.

1. Introduction

Both coronal mass ejection (CME) and the corotating interaction region (CIR) can generate a magnetic storm and substorm (Kilpua et al. 2017). During magnetic storms and substorms, the charged particles precipitate along the Earth’s magnetic field lines through the cusp and polar cap into the upper atmosphere. These charged particles collide with the atoms and molecules in the atmosphere to excite the aurora (Tinsley et al. 1986; Sigernes et al. 2011). The common wavelength bands of the aurora are 427.8, 557.7 and 630.0 nm, corresponding to the colors of blue, green, and red (Tinsley et al. 1986). In mid- and low-latitude areas, the most common color of the observed aurora is red (Tinsley et al. 1986).

The global distribution of the aurora transients has been studied for a long time (Akasofu 1964; Feldstein & Starkov 1967). Statistical results show that the aurora distributes around a geomagnetic latitude of 67°. The auroral oval is a circular belt of the auroral emission around the geomagnetic north and south poles (Akasofu 1964). Several studies have reported that the intensity, brightness, size, and latitude-width of the aurora are affected by the solar wind density, dynamic pressure, and geomagnetic field disturbance (Akasofu 1964; Boudouridis et al. 2003; Shue et al. 2009). The location and size of the aurora can be predicted by different models and methods (Sigernes et al. 2011).

In the case of very strong geomagnetic activity, the low-latitude boundary of the auroral oval moves to the equator, and the width of the oval increases (Sigernes et al. 2011).

Yokoyama et al. (1998) obtained an empirical relation between the Dst index, the equatorward boundary of the auroral oval (EBAO), and the geomagnetic field intensity. In the super magnetic storms of 1859 and 1872, the records show that the red aurora was observed in Mexico (Gonzalez-Esparza & Cuevas-Cardona 2018), Japan, and southern China (Hayakawa et al. 2016, 2018a, 2018c, 2019). As reported in previous works, the most equatorward boundary of the auroral visibility is 20°2 and 20°5 during the magnetic storms in 1859 August and September, respectively (Tsurutani et al. 2003; Hayakawa et al. 2018a). Later, the equatorial boundary of the auroral visibility (EBAV) was updated to be 17°, 10°, and 16° in the superstorms of 1859, 1872, and 1921, respectively (Hayakawa et al. 2019, 2020d).

The official history of China includes detailed literature about continual auroral sightings. The earliest datable record is in 193 B.C. reported by Keimatsu et al. (1968) and Zeng & Jin (1988). The historical auroral records ended in 1911 A.D. (Zeng & Jin 1988; Kawamura et al. 2016). Due to its relatively low geomagnetic latitude, the auroral visibility in China requires more intense magnetic storms and hence the Chinese records are more sensitive to the ICME-storms than the European records (Hayakawa et al. 2020f). Presently, it is very rare to observe the aurora anywhere in China, except for northeastern China (Wu et al. 2016a; Hayakawa et al. 2020b, 2020c). As the city observing aurora most frequently, the geographical position of Mohe is 53°N127°E, and the geomagnetic position is 43°N163°E presently.

Keimatsu et al. (1968) suggested using global-scale auroral records to trace the archaeo-secular variation in the geomagnetic field. Hayakawa et al. (2015) collected the sunspot and the aurora observation (eyewitness) literature from the Song Dynasty of China (960–1279 A.D.). Besides, the auroral
records in Sui, Tang (Stephenson et al. 2019), Five Dynasties and Ten Kingdoms (Tamazawa et al. 2017), Yuan, Ming (Willis & Stephenson 2000; Hayakawa et al. 2017b; Hattori et al. 2019), and Qing (Willis et al. 2007; Kawamura et al. 2016) were systematically studied. While the local histories have been carefully consulted in several studies, such as Willis et al. (2007), the majority of previous studies concentrated on the official histories in search of better long-term homogeneity. In this regard, Zeng & Jin (1988) placed more weight on the local histories after the Ming Dynasty in the interest of being comprehensive, trading off long-term homogeneity. The records were studied to reveal the solar activity at that time. However, it is still unknown whether these historical auroras observed at mid or low latitudes were caused by strong CMEs, as several case studies have revealed CIR-contributions for historical mid-latitude aurorae (Bhaskar et al. 2020; Hayakawa et al. 2020).

The position of the geomagnetic north pole (GNP) and the intensity of the geomagnetic field varied greatly over time (Hyodo et al. 1999). Since the beginning of modern geomagnetic measurements, the field intensity has been reduced by 6% per hundred years (Brown et al. 2018). In the past 10,000 years (10 ka), the archaeomagnetic field measurements have shown that the intensity fluctuation could be 20% of the present value (Korte et al. 2011). In addition, the geomagnetic north pole always moves around the geographic north pole at different speeds (Nilsson et al. 2011).

Above all, both the CIRs and CMEs could generate an aurora observed at mid/low latitudes, as the intensity and GNP of the geomagnetic field varied in history (Richardson et al. 2006; Bhaskar et al. 2020; Hayakawa et al. 2020). It is necessary to separate the auroras caused by CIRs and CMEs, and to identify the strong CMEs that occurred in the historical era before modern measurements, as conducted for the European records during the Maunder minimum (Hayakawa et al. 2020) and Trouvelot’s auroral drawing on 1872 March 1 (Bhaskar et al. 2020). Based on an existing catalog of auroral records in Chinese history (Zeng & Jin 1988), this work calculates the EB AO and the EBAV according to the varied geomagnetic field from 193 B.C. to 1911 A.D. Statistical studies report that CIRs hardly drove magnetic storms with Dst < −161 nT (Gonzalez et al. 1994; Richardson et al. 2006). Thus, the magnetic latitude of the EB AO related to Dst = −161 nT (EBAV_{161}) is used to exclude CIR storms. Furthermore, the magnetic latitude of EBAV related to Dst = −350 nT (EBAV_{350}) is calculated. Since a magnetic storm with Dst < −350 nT is classified as a great-level storm (Loewe & Pröss 1997), the auroras observed at magnetic latitudes lower than EBAV_{350} are candidates caused by great magnetic storms.

Historical records, the archaeomagnetic field model, and the solar wind–magnetosphere interaction model are described in Section 2. The results are shown in Section 3. A discussion is given in Section 4. The conclusion is summarized in Section 5.

### 2. Data and Methods

#### 2.1. Auroral Records in Chinese History

In the 1980s, Chinese philologists and astronomers checked most of the ancient Chinese literature and published a book called “The Collection of Ancient Chinese Astronomical Records” (Zeng & Jin 1988). This book recorded most of the astronomical anomalies in the official history and the local history, including the auroras, sunspots, meteorite, occultation, and eclipses, providing the source of these descriptions in the original text. However, Zeng & Jin (1988) had not consulted diaries and newspapers, which have been consulted in the case studies for individual extreme space weather events (Hayakawa et al. 2018c, 2020b, 2020c). In addition, a possible alternative date in A.D. for the astronomical phenomenon is also provided. All the historical auroral records studied in this work are from both local histories and official histories. So, the time distribution of the auroral records are not homogeneous (Hayakawa et al. 2017b).

![Number of auroral records per 50 years](Image)

**Figure 1.** The time distribution and positions of the 309 historical auroral records. (a) The distribution of the auroral records in time. The number of records is counted every 50 yr. (b) The positions of the major cities observing auroras in history. The position of Mohe is also shown for comparison. It should be noted that the studied auroral records are from both local histories and official histories. So, the time distribution of the auroral records are not homogeneous (Hayakawa et al. 2017b).

#### 2.2. Archaeomagnetic Field Model

To study the relation between the magnetic latitude of the auroral observation and the variation in the geomagnetic field, it is necessary to determine the geomagnetic latitude of China between 193 B.C. and 1911 A.D., as well as the intensity of the archaeomagnetic field. Korte et al. (2011) and Korte & Constable (2011) provided models of the intensity and inclination of the geomagnetic field for the last 3000 yr (3 ka) and 10,000 yr (10 ka). The models are published
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at http://geomagia.gfz-potsdam.de/models.php. In addition, Nilsson et al. (2011) proposed another model for the shift of the GNP, covering a time span of 10 ka.

2.3. Space Weather Modeling Framework

The relation between EBAO, Dst, and the geomagnetic field intensity reported by Yokoyama et al. (1998) is obtained by in situ measurements of modern satellite DMSP, when the geomagnetic field is rather stable. To reveal the effect of varied geomagnetic fields on auroras, the space weather modeling framework (SWMF; Tóth et al. 2005, 2012) is used to simulate the mass and energy transport in the cusp region. Therefore, there are two methods, including the empirical relation and the simulation, to investigate how the varied geomagnetic field in history affects the intensity and boundary of an aurora.

The SWMF integrates a global MHD model BATS-R-US (Powell et al. 1999), a ring current model Rice Convection Model (Wolf et al. 1982; Toffolatto et al. 2003), and an ionospheric electrodynamic solver (Ridley et al. 2004). The model is driven by the interplanetary magnetic field (IMF) and solar wind conditions at the upstream boundary. In the simulation, the geocentric solar ecliptic coordinate system is used. The x component is directed to the Sun from the Earth, the z component is directed to the north, and the y component is the cross product of z and x.

Two groups of parameters of the upstream solar wind are set. Group 1 includes the mean values of the present solar wind. Statistically, the most likely speed of the present measured CMEs is between 400 and 500 km s$^{-1}$ (Gopalswamy 2006; Feng et al. 2018; Song & Yao 2020). The mean solar wind speed has fluctuated around approximately 500 km s$^{-1}$ for the past 400 yr (Owens et al. 2017). Therefore, the solar wind speed in group 1 is set to be 500 km s$^{-1}$. Since the solar wind is from the Sun to the Earth, the velocity of the solar wind is set to $V_s = -500$ km s$^{-1}$. In addition, the magnetic field of the solar wind is critical for generating a magnetic storm. Previous statistical studies reported that the southward IMF is highly related to magnetic storms (Burton et al. 1975; Akasofu 1981; Yermolaev et al. 2010). The magnitude of the southward magnetic field of the CIR driving magnetic storm is approximately 10 nT (Tsurutani et al. 2006). The total magnitude of the magnetic field of the measured CME has a peak distribution between 10 and 15 nT (Gopalswamy 2006; Zurbuchen & Richardson 2006; Li & Yao 2020). In addition, the reconstructed magnetic field of quiet solar wind has fluctuated between 3 and 8 nT in the past 2000 yr, which is similar to the present condition of solar wind (Cliver et al. 2013; Cliver & Herbst 2018). Therefore, the IMF of the solar wind in group 1 is set to $B_z = -10$ nT, which generates the magnetic storm. In summary, both the values of the speed and the southward IMF in group 1 input to the simulation are the mean values of present solar wind to drive magnetic storms.

Group 2 includes the reconstructed parameters of the solar wind in the Maunder minimum (Owens et al. 2017). According to the auroral records, the solar wind speed, the IMF strength, and the proton number density of the representative years are adopted for the simulation. The four auroral records in the years when the solar wind varied significantly are listed in Table 1.

We determine the cusp region by identifying its boundary where the precipitating ion flux is reduced to half of its maximum flux per unit area. It should be mentioned that the tilt angle is positive, when the geomagnetic north pole points to the dayside.

3. Results

3.1. Historical Auroral Records

All 309 historical records are from places close to the following five cities: Xi’an, Hangzhou, Kaifeng, Taiyuan, and Beijing, which are shown in Figure 1. We would like to mention that the studied auroral records are from both local histories and official histories. So, the time distribution of the auroral records is not homogeneous, especially when we use the local histories (Hayakawa et al. 2017b). There is no auroral record in nine periods. And each of them lasts for more than 50 yr. These periods are shown in Table 2. To exclude the social effect, all nine periods are checked carefully according to history. The start and end years of each dynasty are from Wilkinson (2000). Four periods (No. 1, 2, 7, 9) are related to times of peace, three periods (No. 5, 6, 8) cover a very short turbulent time, and two periods (No. 3 and 4) cover a long turbulent time. Except for periods No. 3 and No. 4, the social effect on such a long absence of auroral records could be excluded. The detailed temporal ranges when no sunspot is recorded are also listed in Table 2. To determine if the record vacancies of aurora and sunspot are caused by the war or dynasty change in periods No. 3 and 4, the records of other astronomical phenomena are checked. There are records about meteorites, lunar occultation, and eclipse in Zeng & Jin (1988) in all the nine periods. It is interesting that there is no sunspot record in two periods. In another five periods, there is no sunspot record in part of the interval. It should be mentioned that the sunspot record starts from 28 B.C. in Zeng & Jin (1988). So the sunspot record is marked as Unknown for period No. 1. Only in period No. 7 are the sunspots recorded over almost all of the time.

Moreover, the absence of both aurora and sunspot may indicate the existence of grand minimum in the history. The periods No. 5 and No. 6 are in the same grand minimum in Usoskin (2017) and Usoskin et al. (2007). There are two auroral records in 707 and 708 A.D., otherwise periods No. 5 and No. 6 could be classified into one period. It is sensible for the grand minimum from 650 to 730 A.D. to have only two auroral records. Besides, periods No. 8 and No. 9 are related to the Wolf minimum and Spoerer minimum, respectively (Hayakawa et al. 2017b).

The additional five periods, including No. 1, 2, 3, 4, and 7, have not been reported to be the grand minimum before. Since there are continuous sunspot records in period No. 7, it is not a grand minimum. In periods No. 2, 3, and 4, there is no sunspot record in most of the time. So they are possibly related to grand minima. In period No. 1, the sunspot has not been recorded regularly. It could not be determined if it is a grand minimum. In addition, there are only three auroral records in the period between 1010 and 1070 A.D., when no sunspot is recorded. This period is named Oort minimum deduced from the solar activity reconstructed by cosmogenic isotopes (Usoskin et al. 2007).

3.2. Geomagnetic Latitude of the Observation Sites

The current geographic positions of the four cities in China, Hangzhou, Xi’an, Taiyuan, and Beijing are 30°N119°E, 33.4°N108°E, 37.5°N112°E, and 40°N116°E, as shown in Figure 1(b),
The geomagnetic latitude increased from 200 B.C. to 750 A.D. in China. At that time, the GNP was closer to China than it is at present; therefore, the geomagnetic latitude of Beijing reached a maximum of 40° N, which was the same as its geographical latitude. Similar trends could be identified in Hangzhou, Xi’an, and Taiyuan. From 750 A.D. to 1150 A.D., the geomagnetic latitude of China was stable and high. As reported by Stephenson et al. (2019), the 776 January aurora was observed with favorably close distance from the magnetic pole due to its contemporary position; though, this event is not included in Zeng & Jin (1988). After 1150 A.D., China’s geomagnetic latitude decreased rapidly, as the GNP moved rapidly from Siberia to Canada. This means that the present geomagnetic latitude of China is lower than that in history.

The blue stars in Figure 2(b) represent the geomagnetic latitude of the location where the auroras were observed. The same aurora was frequently observed at different locations. To separate the aurora generated by CIR storms from those generated by strong CME storms, the equatorward boundary of the auroral oval is calculated according to the relation reported by Yokoyama et al. (1998).

\[
E_m = 4/3 \cdot \pi \cdot a^3 B_0^2 / \mu_0
\]  
(1)

\[
E_R = -3/2Dst \cdot E_a B_0
\]  
(2)

\[
E_M = 10(E_R + E_Q)
\]  
(3)

\[
L_e = (8E_M \cdot 10^{17})^{-1/3}
\]  
(4)

\[
\lambda = \arccos(Le^{0.5}).
\]  
(5)

In the equations, \(B_0\) is the intensity of the geomagnetic field with units nT, \(E_Q\) is the energy of the quiet ring current, which is \(4.7 \times 10^{15}\) J. \(\lambda\) is the geomagnetic latitude of the EBAO.

The CIRs hardly generated magnetic storms with \(Dst < -161\) nT (Richardson et al. 2006; Hayakawa et al. 2020). Therefore, the critical value of EBAO and EBAV are related to \(Dst = -161\) nT. The auroras observed at geomagnetic latitudes higher than this critical EBAV are caused by CIRs or moderate CMEs, while those observed at lower latitudes than this critical EBAV are caused by strong CMEs. The blue dashed line represents the equatorward boundary of the auroral oval related to a magnetic storm with \(Dst = -161\) nT. Assuming the altitude of an aurora is 400 km (Roach et al. 1960), input this altitude to

### Table 1

| YYYY | MMDD | C/P      | MLAT(°) | RT                                      |
|------|------|----------|---------|-----------------------------------------|
| 1646 | 0301 | Beijing  | 35      | In the northern clouds there is a red light like a shadow of fire. |
| 1658 | 0127 | Hanshou  | 22      | At dusk, light is in the northeast, like a flame. The light gradually fills the northwest. Red steams shine over the sky, which go out after a while. |
| 1667 | 0212 | Shanghai | 24      | At night, three red beams of light fall vertically into the town like torches, ending in the morning. |
| 1715 | 0421 | Pengpai   | 29      | At night, red light is over the Fushan. |

Note. C/P denotes the city and province. MLAT denotes the magnetic latitude. RT denotes the translation of auroral records.

### Table 2

| NO. | ST   | EN   | DR   | SE               | SP    | EC    | GM   |
|-----|------|------|------|------------------|-------|-------|------|
| 1   | 138  | −33  | 046  | Normal (Western Han) | Unknown | Y     | NR   |
| 2   | 33   | 194  | 162  | Normal (Eastern Han) | PN(20−180) | Y     | NR   |
| 3   | 223  | 291  | 69   | 220−280 Three Kingdoms | PN(188−268) | Y     | NR   |
| 4   | 369  | 429  | 61   | 265−316 Western Jin | PN(400−478) | Y     | NR   |
| 5   | 618  | 706  | 89   | 317−420 Eastern Jin | N(579−826) | Y     | U(650−730) |
| 6   | 709  | 759  | 51   | 420−589 NanBei Chao | N(579−826) | Y     | U(650−730) |
| 7   | 829  | 881  | 53   | Normal (Tang) | Y(832−875) | Y     | NR   |
| 8   | 1262 | 1353 | 92   | 1279 End of Southern Song | PN(1276−1344) | Y     | Wolf(1270−1350) |
| 9   | 1369 | 1448 | 80   | Normal (Ming) | PN(1383−1512) | Y     | Spoerer(1390−1550) |

Note. In this table, ST denotes the start year and EN denotes the end year of the intervals during which no aurora was recorded. DR = EN-ST+1 represents the duration of the intervals in units of years. SE denotes the social event. SP denotes the sunspot number record. EC represents the eclipse record. N means there are no records, and Y means there are records. PN denotes that in part of the interval there is no sunspot record. U represents Usoskin et al. (2007). GM represents grand minimum. NR means no report.
Figure 2. Variation in the geomagnetic latitude of the four cities and geomagnetic latitude of the studied auroral records. (a) Variation in the geomagnetic latitude of Beijing, Taiyuan, Xi’an, and Hangzhou from 193 B.C. to 2000 A.D. (b) The geomagnetic longitude of the auroral records from 193 B.C. to 1911 A.D. The equatorward boundary of the auroral oval (EBAO) related to Dst = −161 nT is shown as the blue dashed line. According to Hayakawa et al. (2018a), the equatorward boundary of auroral visibility (EBAV) related to Dst = −161 nT is 15° less than the EBAO, which is shown as the black dashed line. The blue stars represent the magnetic latitude of all the historical records. The EBAO related to Dst = −350 nT is shown as the green dashed line. And the EBAV related to Dst = −350 nT is shown as the red dashed line.

Equation (1) in Hayakawa et al. (2018a), the equatorward boundary of auroral visibility is approximately 15° less than the magnetic latitude of the EBAO. Therefore, the EBAO during a magnetic storm with Dst = −161 nT is shown as the black dashed line in Figure 2(b). Furthermore, the EBAO and EBAV related to magnetic storms with Dst = −350 nT are also calculated, shown as green and red dashed lines in Figure 2(b), which can be used to select great-storm CMEs. Since the geomagnetic latitude of China decreased substantially after 1500, there were some auroras observed below the critical EBAV_{350} (red dashed line in Figure 2(b)).

In modern times, after the great aurora was displayed in two intense geomagnetic storms in 1938 and 1941 (Hayakawa et al. 2020b, 2020c), the regular recording of an aurora observed by naked eye in China started in 1956, which was carried out by the China Meteorological Administration. Mohe is a city in northeast China with the most common aurora sightings since 1956 (Wu & Zhang 2006; Wu et al. 2016a). There are a few records in other lower-latitude cities observing the aurora by naked eye in the 1950s and 1980s (Lin 1982; Zhang 1983; Zhu 1983; Li & Cheng 1985; Wu et al. 2016b).

3.3. Effects of Varied Geomagnetic Field and Solar Wind

The variations in the geomagnetic field intensity and inclination in the four cities are shown in the top panel of Figure 3. It is obvious that the trends in the four cities are quite similar. In the past 2000 years (2 ka), there are three intervals showing weaker geomagnetic fields than the present intervals. There is a distinct valley in the inclination angle around the 17th century. This is caused by the substantial movement of the GNP from Siberia to Canada. However, the inclination variation does not perfectly match the movement of the GNP. A possible explanation is that the geomagnetic field contains high degree terms of the spherical harmonics.

To investigate the effect of varied geomagnetic fields and varied solar wind conditions on the flux of precipitating ions through the polar region, the SWMF is used to simulate the ion flux from both the dayside and nightside magnetosphere. When the solar wind condition is at the present mean level (group 1), the geomagnetic field geometry and the ion flux in the simulation are shown in Figure 4. The black solid circle has a radius of 1.2 Earth radii ($R_e$). The blue dashed circle has a radius of 3 $R_e$. The positive flux indicates the downward moving ions. The negative flux indicates the upwelling ions. Both the maximum flux per unit area (peak flux) and the integrated flux within the cusp area (total flux) are positive. The first panel shows the results with a reduced intensity of the geomagnetic field (i.e., 80% of present intensity), when the tilt angle is 0°, 15° to the dayside, and 15° to the nightside. The second panel shows the results under an enhanced geomagnetic field (i.e., 120% of the present intensity).

When the solar wind condition is stable, the variations of the ion flux and the cusp area are affected by the intensity and tilt angle of the geomagnetic field, shown in Figure 5. When the tilt angle is between −15° and 15°, stronger geomagnetic field...
leads to the increase of the cusp area, and the total flux of the cusp area. The relation between geomagnetic field intensity and the flux of the precipitating ions through the polar region obtained from the simulation is in accordance with that between the geomagnetic field intensity and the EBAO (Yokoyama et al. 1998).

According to the reconstruction from Owens et al. (2017) and McCracken & Beer (2015), the speed, the number density, and the IMF of the solar wind in the past 400 yr could be obtained. It should be noted that the reconstructed solar wind parameters in Maunder minimum (1645–1715) and Dalton minimum (1797–1827) (Usoskin 2017; Hayakawa et al. 2020a) are quite different from the present mean values. In our study, the parameters in group 2 are related to Maunder minimum. The reconstructed solar wind parameters in each of the 10 yr, when there is an auroral record, are shown in the second and third panels of Figure 3. The simulation results for Maunder minimum including the cusp area, the peak flux per unit area, and the total flux of ions within cusp. Their variations over time from 1645 to 1715 are shown in the last two panels of Figure 3.

The solar wind parameters and the simulation results for the 10 selected years are shown as triangles in Figure 3. The whole trend from 1645 to 1715 is obtained by the nearest interpolation, shown as curved lines. It could be identified that there are four turning points, which control the whole trend shown in Figure 3. They are in 1646, 1658, 1667, and 1715, with the auroral records listed in Table 1. The magnetic field geometry and the ion flux in the simulations of these four events are shown in Figure 6.

From Figures 3 and 6, it could be identified that the stronger southward IMF is related to larger cusp area in the nightside, while higher speed and proton number density are related to smaller cusp area in the nightside. The fluctuation of cusp area in the dayside is smaller, showing a similar trend as that at the

Figure 4. The simulation of solar wind interacting with the Earth’s magnetosphere with varied geomagnetic field. The speed, proton number density, and southward interplanetary magnetic field of the solar wind are $V_x = -500 \, \text{km} \, \text{s}^{-1}$, $N_p = 10 \, \text{cm}^{-3}$, and $B_z = -10 \, \text{nT}$. The top panel and the bottom panel show the results when the geomagnetic field intensity is 4/5 and 6/5 of the present value. From left to right, the results are related to tilt angles of 0°, 15° to the dayside, and 15° to the nightside. The geomagnetic field is represented by the black line. The flux of ions per unit area (density multiplied by the velocity) is shown by color from blue to red in units of $10^9 \, \text{cm}^{-2} \, \text{s}^{-1}$. In addition, the color bar is on the right of each subfigure.

Figure 5. Simulated flux of ion injection from the magnetosphere with the varied geomagnetic field. The peak flux is the maximum flux of ions per unit area ($N \cdot V$), which is shown as a blue line. The total flux is the integrated ion flux in the whole cusp area, which is shown as a green line. The cusped area is represented by the red line. The unit of peak flux is $10^9 \, \text{cm}^{-2} \, \text{s}^{-1}$. The area is in units of square of Earth radii $R_E^2$. The unit of total flux is $10^5 \, R_E^2 \, \text{s}^{-1}$.
nightside. The maximum ion flux per unit area (PF) increases with the proton density of solar wind. The calculated cusp area is at the altitude of 3 Earth radii (Re), which is marked as a dashed circle in Figure 4 and in Figure 6.

For easy comparison, we also calculate the cusp area, maximum flux per area, and the total ion flux of present solar wind and geomagnetic field. The results are CA$^+$ = 0.70, CA$^-$ = 1.42 Re$^2$; PF$^+$ = 850.08, PF$^-$ = 625.50 \times 10^5 \text{cm}^{-2} \text{s}^{-1}; TF$^+$ = 439.39, and TF$^-$ = 620.26 \times 10^5 \text{Re}^2 \text{s}^{-1}. It could be identified that the downward ion flux at nightside decreases a lot in the Maunder minimum. The total ion flux in cusp area is about half of that under present solar wind conditions. But the cusp area stays in a similar range as the present one.

4. Discussion

According to the magnetic latitude of the EBAV$\_161$ shown in Figure 2, whether the recorded aurora was caused by CIRs, moderate-storm CMEs or great-storm CMEs could be classified. Previous statistical works report that CIRs could generate magnetic storms with $-30 \text{nT} > \text{Dst} > -161 \text{nT}$ (Gonzalez et al. 1994; Richardson et al. 2006). Since a stronger magnetic storm leads to a lower magnetic latitude of the EBAO and the EBAV, as shown in Figure 2(b), the auroras observed below the black dashed line could not be driven by CIRs.

Before 1500 A.D., when the magnetic latitude of China was higher than that at present, most of the observed aurorae were caused by CIRs and moderate CMEs. After 1500 A.D., the GNP moved to Canada. This caused the geomagnetic field latitude of China to decrease considerably. Meanwhile, the field intensity decreased to its minimum value in the last 2000 yr. Under these conditions, it would have been very rare to observe the aurora in most places in China after the 16th century, just like the present case (Wu et al. 2016a, 2016b; Hayakawa et al. 2020b, 2020c). However, this provides the best opportunity to investigate the existence of great-storm CMEs, which generate a wider auroral belt and equatorward shift of the EBAO and the EBAV (Boudouridis et al. 2003; Shue et al. 2009; Sigernes et al. 2011). If auroras were observed in China at lower magnetic latitudes than the EBAV related to the great storms, this indicates that the strong CMEs occurred. To quantify our
results, we applied the classification of magnetic storms at the great level having Dst < −350 nT (Loewe & Prölls 1997). According to the EBAV of the great level shown as the red dashed line in Figure 2(b), the auroras caused by great-storm CMEs could be identified, which were below the red dashed line. Surprisingly, there were many great-storm CMEs between 1500 and 1900, when Spörer minimum (1390–1550), Maunder minimum (1645–1715), and Dalton minimum (1797–1827) were inside (Lean et al. 1995; Solanki & Fligge 2000; Usoskin et al. 2015; Cliver & Herbst 2018; Hayakawa et al. 2020e). There were auroral sighting records in the same year, such as 1620 and 1646, from different places in China. As previously reported by Hayakawa et al. (2018b) there were simultaneous auroral records on the same day from different places in China in 1730. There are quite a few studies about the aurorae in September 1770 (Willis et al. 1996; Ebihara et al. 2017; Hayakawa et al. 2017a). Apart from the case analyses for extreme space weather events (Hattori et al. 2019; Isobe et al. 2019), our results indicate that there are more great-storm CMEs in the past 400 yr. Some of the great-storm CMEs happened in the solar maximum years, and some happened in the solar minimum years, as shown in Figure 7.

5. Conclusion

This work excludes CIRs and identifies great-storm CMEs by studying historical auroral observation (eyewitness) records in China from 193 B.C to 1911 A.D., with archaeomagnetic field models and the 3D solar wind–magnetosphere interaction simulation. In the past 2000 yr, the GNP has shifted from Europe to Siberia and finally to Canada. As a result, the geomagnetic latitude and the geomagnetic inclination of China has varied greatly. In addition, the intensity of the geomagnetic field has fluctuated by approximately 20%.

According to the relation between EBAO, Dst, and the geomagnetic field intensity (Yokoyama et al. 1998), the critical EBAV related to magnetic storms with Dst = −161 nT in history are calculated. Since CIRs cannot generate Dst < −161 nT, the above critical boundary is used to exclude CIR storms. Most of the recorded aurora sightings were generated by CIR storms or moderate CME storms before 1500 A.D., with strong CME storms occurring occasionally. After 1500, the shift of the GNP decreased the geomagnetic latitude of China, which provided an opportunity to investigate the existence of great-storm CMEs. In this paper, great-storm CMEs are supposed to generate magnetic storms at the great level, which is related to Dst < −350 nT. According to Cliver & Dietrich (2013), the Carrington event probably caused Dst to decrease to −900 nT. The stronger CMEs lead to lower latitudes of the EBAO and EBAV. In our study, the lowest magnetic latitude of the historical auroral records is at 10°.

Compared with the reconstructed sunspot number, the deduced great-storm CMEs meet the maximum sunspot number in 13 solar cycles between 1610 and 1910. The remaining great-storm CMEs occurred during descending years or even solar minimum years. Our work supports the idea that great-storm CMEs may occur in solar minimum (Kilpua et al. 2015; Ribeiro et al. 2016; Hayakawa et al. 2020e) and the temporal cadence of great-storm CMEs is not constant.

In addition, the effect of the geomagnetic field intensity on the EBAO and on the flux of precipitating ions are studied. The EBAO moves to lower latitudes with stronger geomagnetic fields. The extent of the movement increases with Dst. Under the present solar wind condition, the precipitation process in the polar region from both the dayside and nightside are simulated with varied geomagnetic fields. Both the ion flux and the cusp area increase under the stronger geomagnetic field for tilt angle between −15° and 15°. The effects of the solar wind variation on the cusp area and the downward ion flux are also studied. When the solar wind condition is set to be that in the Maunder minimum, the simulation results show lower flux of downward propagating ions, but similar cusp area to that at present. This implies that the brightness of aurora is weaker (Hayakawa et al. 2020b), but the equator boundary of the aurora oval stays at a similar latitude to that at present. Therefore, our simulation results suggest that it is sensible to observe (eyewitness) aurora at mid/low magnetic latitude during grand minima, though the brightness of aurora is about half of that at present.

Finally, we report the possible grand minima in history. There are nine periods showing no auroral records. In seven of the nine periods, the sunspot is not recorded for the whole or the part of the interval. Since the records of solar and lunar eclipses are available, the absence of auroras and sunspots may indicate the grand minima (see also Hayakawa et al. 2017b). The seven possible grand minima deduced from the historical auroral records are related to four of the revealed grand minima by cosmogenic isotopes (Usoskin 2017).

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