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Key Points:
- We solved the long-standing mystery of the red aurora painting of 17 September 1770
- The painting of red aurora and a newly discovered detailed diary play complementary roles to evaluate the largest magnetic storm in history
- We can learn the physics behind the extreme magnetic storm, thanks to the citizen science 250 years ago

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Inclined Zenith Aurora over Kyoto on 17 September 1770: Graphical Evidence of Extreme Magnetic Storm

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Abstract Red auroras were observed in Japan during an extreme magnetic storm that occurred on 17 September 1770. We show new evidence that the red aurora extended toward the zenith of Kyoto around midnight. The basic appearance of the historical painting of the red aurora is geometrically reproduced based on the inclination of the local magnetic field and a detailed description in a newly discovered diary. The presence of the inclined zenith aurora over Kyoto suggests that the intensity of the September 1770 magnetic storm is comparable to, or slightly larger than that of the September 1859 Carrington storm.

1. Introduction

The auroral oval expands equatorward during magnetic storms, and the expansion is related to the intensity of the storm (Akasofu, 1964; Akasofu & Chapman, 1963). The relationship has been investigated in detail for modern intense magnetic storms as indicated by the *Dst* index of –25 nT $> Dst > -600$ nT (Yokoyama et al., 1998) or for relatively moderate magnetic storms with the *Sym-H* index of 100 nT $> Sym\text{-}H > -250$ nT (Milan et al., 2009), where more negative *Dst* or *Sym-H* values indicate stronger ring current of magnetic storms. However, it has been unknown how much the aurora can extend to low latitudes during the largest storms. Interpreting the historical records of red auroras in low latitudes has therefore been a long-standing problem of great importance, especially in terms of allowing the modern society to mitigate possible severe damages to power grids during intense magnetic storms (Kataoka & Ngwira, 2016). The largest magnetic storm of the past 200 years occurred on 1–2 September 1859, when red auroras were observed in tropical areas at approximately 20° magnetic latitude (Green & Boardsen, 2016), associated with the so-called Carrington flare (Carrington, 1859).

In Japan, the most extreme aurora sightings were not those of the September 1859 event. The largest number of historical documents reporting red auroras was reported on 17 September 1770 (Matsushita, 1956). The September 1770 event occurred during the equinox season, when the magnetosphere and ionosphere tend to develop intense storms (Bartels, 1932; McIntosh, 1959; Russell & McPherron, 1973; Yoshida, 2009). The event also occurred during a new moon period, which led people to watch this special nighttime event in detail. The September 1770 event continued for at least three successive days over China from 16 September 1770 (Willis et al., 1996; Willis & Stephenson, 2002). In the Southern Hemisphere, the Aurora Australis was also observed on 16 September 1770 during the first voyage of Captain James Cook to Australia (Willis et al., 1996; Willis & Stephenson, 2002). It therefore seems that the Asian longitude was at the right place and at the right time to repeatedly observe the peak activities of the magnetic storms for several hours around the local midnight. The event occurred around the time of the maximum period of solar cycle 2 (1766–1775), and the prolonged low-latitude auroral activity during the solar maximum is also consistent with its historical occurrence (Kataoka et al., 2017). Based on these perfect conditions, the September 1770 event is a unique event, although the strength of the September 1770 magnetic storm has not yet been estimated in previous studies. It is the purpose of this study to report new graphical evidence of the zenith aurora over Kyoto, which is useful to estimate the intensity of the September 1770 magnetic storm.

2. Painting of the Red Aurora of 17 September 1770

We identified the most detailed painting of the red aurora in the premodern Japanese manuscript titled "Seikai," which is owned by the Matsusaka City. Seikai is a book written by Jyuryouan-Syuin just after the

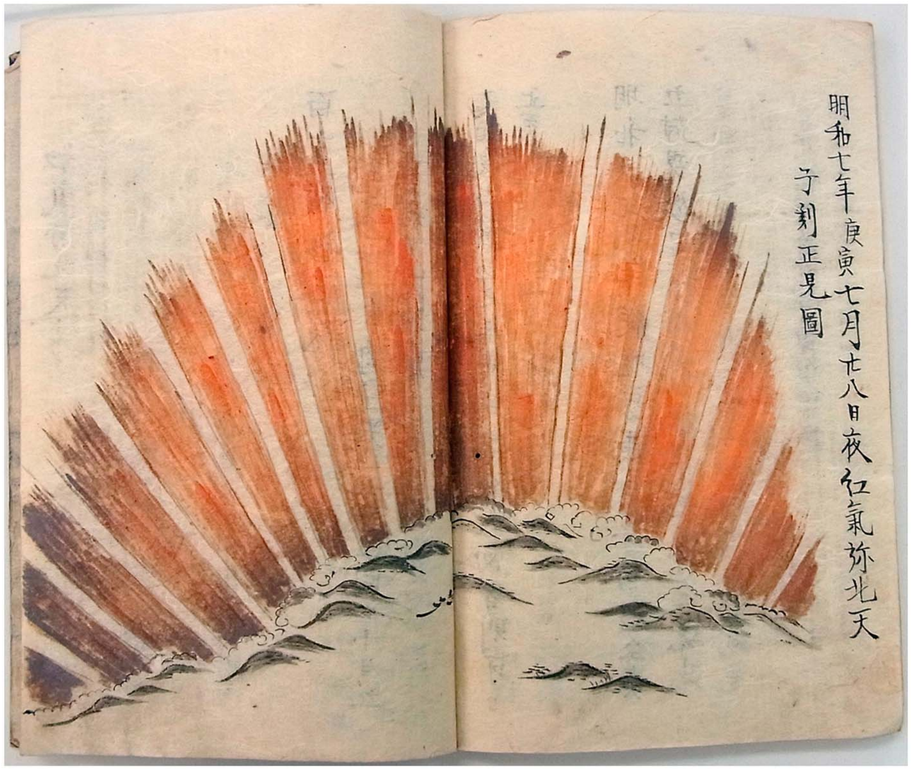

Figure 1. The painting of the red aurora of 17 September 1770 in the premodern Japanese text “Seikai,” which is owned by the Matsusaka City. A radial structure of stripes is shown, comprising small-scale rays inside the stripes. The bottom section and eastern/western edges of the stripes are somewhat darkened. The caption on the right-hand side may be translated as follows: “*On 17 September 1770, at night, red vapor was active at northern sky. The figure was as it watched at midnight*.”

September 1770 event, copied by amateur astronomers, and then widely distributed to public. In eighteenth century Japan, important books were distributed by hand copies. The meaning of the word Seikai itself is “understanding comets.” Its major content is a commentary on comets discovered by Messier. In the second half of this book, there is also a description of fortune telling using the shape of comets. The description of the red aurora is written as an additional section at the very end of this book. Kogan Murai, a book shop owner in Kyoto, donated this book to Ise Jingu Hayasizaki Bunko, the current Jingu Bunko. Now, it is owned by the Matsusaka City. Although other copies of this book are held in Tohoku University located at Sendai City and in Jingu Bunko located at Ise City, we carefully compared each other and identified that the one of Matsusaka is the clearest (detailed representations of the painting are consistent with the corresponding description), oldest (dedicated to Jingu Bunko in 1861, Tohoku University in 1858, and Matsusaka City in 1770–1784), and therefore is the closest to the original. Note here that Nakazawa et al. (2004) showed a similar figure from the one in Tohoku University.

Figure 1 shows the painting of the red aurora in Seikai, in which an impressive radial structure of stripes comprising small-scale rays is shown, with the bottom section being somewhat darkened. The corresponding description of the painting of the red vapor exists at different pages in Seikai, which may be translated as follows.

> “On the night of the 7th month and 28th day, the sky turned red from west to east across the mountains to the north. People thought it was a big fire. On the northern side of the mountain, there are Ohfuse, Yamasu, and five villages in Kutanoshou, and the population is not large. I saw the sky and thought that this was probably a big fire in the Wakasa country. However, Wakasa should not be burning down all at once. Obama, the castle town of Wakasa, has a large population. But will it all burn down at once? There must be areas of fast and slow propagations of the fire. (This section has been partially omitted) At around 2 a.m., when looking at the sky, the sky in the northeast was still active.

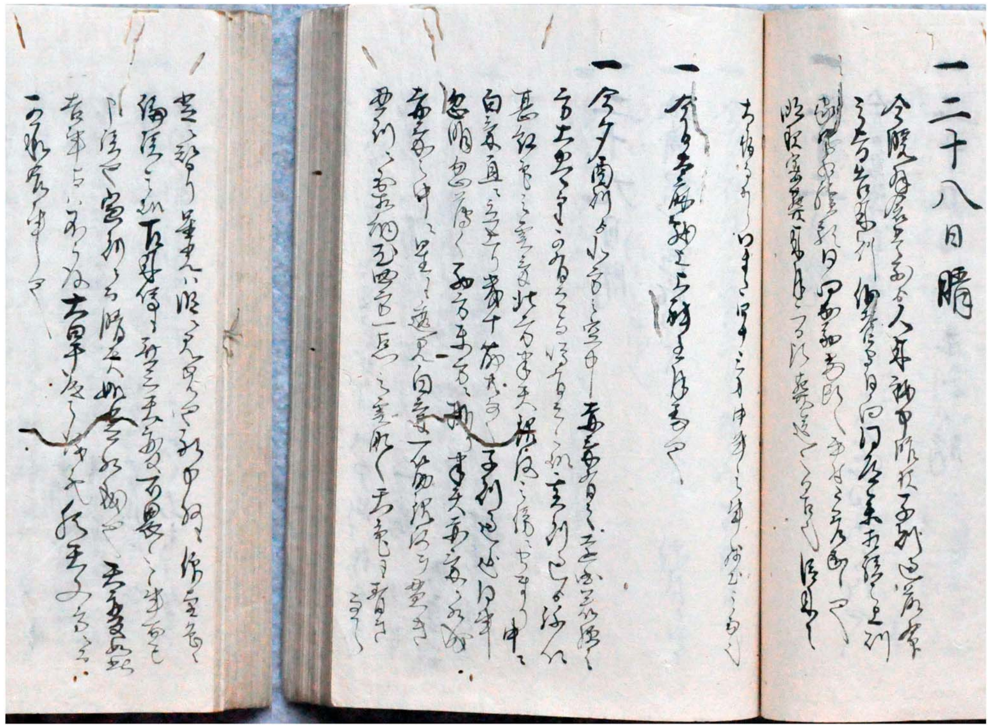

Figure 2. The diary of the Higashi-Hakura family (page 86a-b, call number B2-164), which is owned by the Azumamaro Jinja in Kyoto. The appearance of the zenith aurora over Kyoto on 17 September 1770 is described in detail with references to the position of the Milky Way.

> There were red streaks within the red, as if floating clouds covered the sky before sunset and concealed the sun, and the rays of the sun leaked from behind the clouds."

Note here that the 7th month and 27th day indicate the date of 17 September on the western calendar. Ohfuse, Yamasu, and Kutanoshou are in the northern part of the Kyoto prefecture, while Wakasa country is the whole Fukui prefecture, excluding the Tsuruga city. Therefore, the location of the author was identified as Kyoto.

3. Diary Describing the Red Aurora of 17 September 1770

Although many important premodern Japanese texts and documents are privately owned, increasing number of hidden premodern Japanese texts and documents are being made available for academic research. Through this process, we recently found the detailed diary of the Higashi-Hakura family describing the red aurora on 17 September 1770 at the Azumamaro Jinja in Kyoto. The Higashi-Hakura family had worked as Goten-Azukari administrators of the Fushimi-Inari-Taisya in Kyoto, where many other cultured people also gathered (Tamazawa et al., 2017). The sophisticated description of the red aurora is what would be expected for a person of culture. The diary was written by Nobusato Hakura, a Kokugakusha (a scholar of ancient Japanese thought and culture) living in Kyoto. He was a nephew of Kadano Azumamaro, who was a significant Kokugakusha. He excelled in Chinese Poetry and Japanese Poetry. Therefore, he accurately captured the relative positions of the Milky Way and aurora by poetry expressions.

Figure 2 shows the newly discovered diary of the Higashi-Hakura family, in which the position of the red aurora is described relative to the Milky Way. The standard astrometry therefore works to identify its coordinate. The descriptions of the aurora may be translated as follows.

> "Today, at around 6 p.m. in the evening, red vapor appeared in the northern sky. It was rumored that the direction of the distant Wakasa country is colored like a flame. After around 10 p.m., it became redder and red clouds covered half of the sky to the north, toward the Milky Way; a number of white

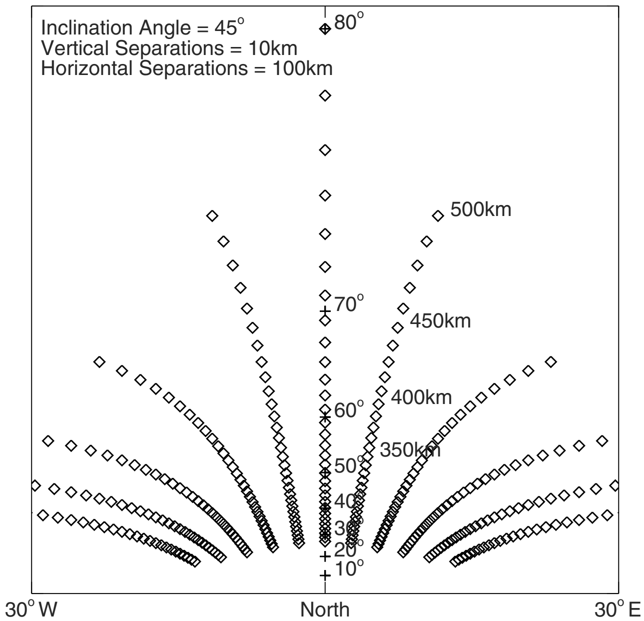

Figure 3. The modeled geometry of the auroral appearance as seen from Kyoto on 17 September 1770. Diamonds show the positions of the red aurora tangentially mapped to the flat plane of the 60° by 80° field of view, plotted every 100 km in east-west direction and every 10 km in vertical direction. The main body of the emissions is assumed to be in the range of 200 km to 500 km, with an inclination angle of 45° along the local magnetic field. Elevation angles are shown by angle markings on the vertical axis with plus signs.

vapors rose straight through the red vapor, and that state continued until around midnight. The red color sometimes suddenly became bright or suddenly became thin, to the west and to the east, and half of the sky was covered by the red vapor. In the red vapor, we can see the stars; a single white vapor penetrated through the Milky Way, and settled around 2 a.m. (This section has been partially omitted) People in the shrine looked up to the sky and discussed various things, saying that this was horrible because the vapors had rarely been heard of in the past. The sky was clear and returned to normal around 4 a.m. This is a kind of a natural disaster; I do not think it is a very good thing. It is surely because of a spell of dry weather. It is something to ask the astronomers of the Tokugawa Shogunate."

It is noted that both Seikai and the diary of the Higashi-Hakura family show that the aurora was toward Wakasa and to the north, and that small-scale rays appeared within the large-scale stripes. Therefore, both observers were likely in Kyoto and looking at the same aurora. There is only one notable discrepancy about the activity at approximately 2 A.M. One said it was active while another said it had settled. The discrepancy can be understood by the ambiguity of the definition of time, that is, the definition of the word "around 2 A.M.", which means during the time interval from 1 A.M. to 3 A.M.

4. Reconstructed Geometry of the Red Aurora on 17 September 1770

The standard astrometry helps to reconstruct the elevation angles of the Milky Way, as viewed from Kyoto on 17 September 1770. For example, within the Milky Way, Cygnus was located at the zenith at 8–9 P.M. on 17 September, while Cassiopeia was located at a 60°–70° elevation angle at 0–2 A.M. on 18 September. The diary's descriptions of the red aurora covering half of sky with some structures penetrating the Milky Way is therefore consistent with the astrometry, and thus, the red aurora likely did extend to the zenith of Kyoto.

The magnetic latitude of Kyoto (35.0°N, 135.7°E) was approximately 24.3° ± 0.6°, as estimated from the reconstructed tilt of the dipole axis, with the north pole at (79° ± 0.5°N, 300° ± 3.0°E) in 1770 (Korte & Constable, 2011). The inclination and declination angles of the local magnetic field of Kyoto are estimated to be 44.5° ± 1.5° and 0.99° ± 0.03°, respectively, where the above errors are all evaluated from the bootstrap method (Korte & Constable, 2011). To understand the basic appearance of the red aurora from Kyoto, we consider a Cartesian box model (*X* to the east, *Y* to the north, and *Z* to vertical), omitting the effect of the Earth's curvature for simplicity. The red aurora is assumed to be located over Kyoto at an inclination angle of 45° along the local magnetic field. We further assume that the main body of the red aurora emission ranges from 200 km to 500 km altitudes, based on space-age observations of the red line emission of the excited atomic oxygen state of O(1D) (Shiokawa et al., 1997).

Figure 3 shows an example of the calculated geometry of the red aurora as seen from Kyoto, based on the magnetic field model and the description of the diary as shown in previous sections. The plotted diamonds show the position of the red aurora, with steps at every 100 km in the east-west direction and at every 10 km in the vertical direction. The basic appearance is consistent with the painting of Seikai, in which the radial structure of stripes with the darkened bottom section is reproduced. Based on their similarity, the best possible interpretation is that the red aurora was at the zenith with the inclination angle of 45°; thus, the separation of stripes was approximately 100 km. The stripes with some substructures of small-scale rays imply the side views of basic auroral structures of spirals, folds, and curls (Hallinan, 1976). The dark colors seen to the east and west in Figure 1 are also reasonable because the relatively distant auroras at the eastern and western edges of the sky were more affected by atmospheric extinctions.

Matsushita (1956) showed that there are at least 15 independent reports of aurora on 17 September 1770 as broadly ranging from west Japan to north Japan. The zenith aurora at 500 km altitude over Kyoto could be seen from distant places of more than 1,500 km apart from Kyoto, that is, essentially everywhere in Japan, which is consistent with every known witness record of 17 September 1770 (Matsushita, 1956; Nakazawa et al., 2004).

5. Discussions

The strength of the September 1770 magnetic storm is estimated based on the presence of inclined zenith aurora over Kyoto. To determine the equatorward boundary of the aurora, the zenith aurora at a 500 km altitude must be mapped to the 200 km ionosphere at approximately 3° to the north from the observed position of a 24° magnetic latitude, along the local magnetic field of 45° inclination angle. The magnetic latitude of the foot point of the aurora is then found to be 27°. Assuming the dipolar magnetosphere, the magnetic latitude of foot point λ and the L value corresponding to the equatorward boundary of the red aurora is expressed as

$$L_e = \cos^{-2}\lambda. \tag{1}$$

The magnetic field energy external to the sphere with radius L_e can be approximated as follows (Yokoyama et al., 1998).

$$E_M = 4\times10^{17}\left(\frac{L_e}{1.26}\right)^{-3}\left(\frac{B_o}{3\times10^4\text{nT}}\right)^2 \text{ J}, \tag{2}$$

where B_0 represents the magnetic field at the surface at the equator. The ring current energy can be related to the *Dst* index as follows (Dessler & Parker, 1959):

$$E_R = 4\times10^{16}\left(\frac{-\text{Dst}}{1000 \text{ nT}}\right)\left(\frac{B_0}{3\times10^4 \text{ nT}}\right) \text{ J}. \tag{3}$$

Space-age observations of precipitating aurora electrons from more than 400 magnetic storms for the time interval from 1983 to 1991 show that the ratio of the ring current energy to the magnetic field energy, ε, is typically 10% (Yokoyama et al., 1998). Using equations (1)–(3), the peak *Dst* index of the magnetic storm with auroral foot point at a magnetic latitude of 27° is estimated to be

$$Dst = -1.0\times10^3\left(\frac{\varepsilon}{10\%}\right)\left(\frac{L_e}{1.26}\right)^{-3}\left(\frac{B_0}{3\times10^4 \text{ nT}}\right) \text{ nT}. \tag{4}$$

To estimate the strength of historical magnetic storms, we need a correction in the magnetic field B_0 of equation (4) because the Earth's dipole moment has decreased especially for the past 300 years (Korte & Constable, 2011). The low-latitude limit of the possible "rays to the north reach to the zenith" aurora was also reported for a magnetic latitude of approximately 24° during the September 1859 storm (see Kimball, 1960, Figures 6 and 7). Applying a correction for the 7.4 ± 0.5% larger Earth's dipole moment in 1859 than in 1980–1990 (Korte & Constable, 2011), the peak *Dst* index becomes approximately -1.1×10^3 nT, which is not inconsistent with the other estimations, which range from −850 nT (Siscoe et al., 2006) to −1760 nT (Tsurutani et al., 2003). Note also that the Earth's dipole moment in 1770 was 14 ± 3% larger than in 1980–1990 (Korte & Constable, 2011), which is used to compare September 1770 and September 1859 events.

The strength of the September 1770 storm would therefore be 3–10% larger than that of the September 1859 storm, as considering the decreasing trend of the Earth's dipole moment from 1770 to 1859, assuming the magnetic latitudes of the zenith auroras are the same at 24° magnetic latitude and the same ratio ε for two different storms, although the actual magnitudes of two magnetic storms might have been comparable considering the event-to-event uncertainties of the ratio ε. Although it is beyond the scope of this study, it would be interesting to develop a self-consistent magnetosphere-ionosphere simulation to quantitatively evaluate and test the minimal model proposed in this study, that is, equation (4), to further understand the saturation mechanism of magnetic storms and the physics behind their dependences on the low-latitude limits of red auroras.

This event preceded human dependence on the electricity, and it is hard to identify damage to available technologies during the September 1770 event, in contrast to the widely observed technological effects during the September 1859 event (Boteler, 2006). If another extreme magnetic storm with the same ring current energy as the September 1770 event occurred today, given the relatively weak current Earth's dipole moment, the auroral foot point extends to the magnetic latitude of 24°, and the zenith aurora would appear over Hawaii (19°N, 154°W), at 20° magnetic latitude. The stripes and rays, possibly the side views of spirals and folds/curls, may imply the existence of strong auroral currents. It has also been discussed that the September 1770 auroras are different from stable auroral red arcs (Nakazawa et al., 2004). The power grids in low latitudes, and even some in such tropical areas, must prepare against possible worldwide blackouts caused by geomagnetically induced currents, which we have recently experienced at high and middle latitudes (Pulkkinen et al., 2005), including South Africa (Gaunt & Coetzee, 2007).

It is also noteworthy that the September 1770 event and the September 1859 event occurred within a time interval of only 100 years, and more than 150 years have already passed since the 1859 event. The probability of another extreme magnetic storm during next 10 years will be lower than 4% under the current decreasing solar activity (Kataoka, 2013), although the simplified approach includes very large uncertainty (Riley & Love, 2017). The probability even becomes negligible if the solar activity continues to decline into another grand minimum (Lockwood, 2013), since the recent study of historical events showed that there were no prolonged auroral events during the grand minimum (Kataoka et al., 2017). However, this is a matter of a high-risk and low-probability natural hazard in the space age, and it is still possible for us to prepare against an unlikely but possible perfect magnetic storm in the future.

From the historical point of view, the authors of the painting and diary can be regarded as amateur astronomers who recorded the surprising phenomena in detail. It was unexpected that we can learn the physics behind the extreme event, thanks to the citizen science 250 years ago. We hope this work represents an example of the importance of interdisciplinary collaborative research, utilizing deep understandings of science and history, which are both necessary to reveal the remarkable facts pertaining to the largest magnetic storms in history.

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