Historical Auroras in the 990s: Evidence of Great Magnetic Storms

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Abstract A significant carbon-14 enhancement has recently been found in tree rings for the year 994, suggesting an extremely strong and brief cosmic ray flux event. The origin of this particular cosmic ray event has not been confirmed, but one possibility is that it might be of solar origin. Contemporary historical records of low-latitude auroras can be used as supporting evidence of intense solar activity around that time. We investigate previously reported as well as new records that have been found in contemporary observations from the 990s to determine potential auroras. Records of potential red auroras in late 992 and early 993 were found around the world, i.e. in the Korean Peninsula, Saxonian cities in modern Germany, and the Island of Ireland, suggesting the occurrence of an intense geomagnetic storm driven by solar activity.

Keywords Sun · Extreme space weather events · Magnetic storm · Historical documents · Carbon-14 spike

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1. Introduction: Carbon-14 Variations in 994

The intensity of a solar flare and its resulting space weather hazards are important issues from both academic and practical points of view. The most intense solar flare and its associated geomagnetic storm recorded by modern telescopic observation was the so-called Carrington event in 1859 (Carrington, 1859; Tsurutani et al., 2003; Hayakawa et al., 2016b; Lakhina and Tsurutani, 2016). The total energy of the Carrington event was estimated to be $\lesssim 10^{32}$ erg (Tsurutani et al., 2003). We have only limited information on the scale of individual solar flares before this event. On the other hand, Maehara et al. (2012, 2015) discovered extremely strong “superflares” in solar-type stars (G-type stars with slow rotation), whose estimated energy is $10^{33–35}$ erg. Based on theoretical arguments, Shibata et al. (2013) suggested that such superflares may also occur on the Sun. Independently, Miyake et al. (2012) and Miyake, Masuda, and Nakamura (2013) found sharp increases in carbon-14 in tree rings from 774 to 775, and from 993 to 994, suggesting significant enhancements in incidental cosmic rays at Earth, which was also supported by the increase in other cosmic-ray-induced radioisotopes in ice cores, such as beryllium-10 and chlorine-36 (Mekhaldi et al., 2015).

Some studies examined contemporary historical documents to determine whether they provide any evidence of these carbon-14 spikes, as historical documents sometimes involve records of auroras as proxies of solar activity (Vaquero and Vázquez, 2009), up to BCE567 as a literal record and up to 771/772 with drawings (Stephenson, Willis, and Hallinan, 2004; Hayakawa et al., 2016c, 2016d). While the former event in 774/775 became widely discussed (e.g. Usoskin et al., 2013; Stephenson, 2015; Neuhäuser and Neuhäuser, 2015; Chapman et al., 2015; Hayakawa et al., 2016a), the latter event received far less attention and has only been discussed by Hayakawa et al. (2015) and Stephenson (2015). For the first event, Hayakawa et al. (2015), examined Chinese official history and found no relevant records between 988 and 996, but suggested a possibility of records in 992 in the Ulster Annals (Annaíla Uladh) and in German chronicles (Fritz, 1873) that might be related with this event. For the second event, Stephenson (2015) examined pertinent Chinese records. He also introduced one Korean record from Goryeosa (hereafter, GRS)\(^1\) and two German records that were referred to in the catalog by Link (1962).

Previous studies detected a cluster of aurora records in the 990s. Fritz (1873) compiled an aurora catalog from ancient time to 1873 that shows the dates of auroral candidates observed in Germany on 992.04.17, 992.10.21, 992.12.24, 993.01.07,\(^2\) and 993.12.26. Link (1962) revisited the original chronicles and recompiled a new catalog that included data until 1600, in which he integrated the data from 992.10.21 and 993.12.26, since the records are quite similar to one another and should have the same origin, except for the event 992.10.21. Lee et al. (2004) compiled catalogs of auroras and sunspots in Korean historical documents and showed an auroral candidate that might have been observed in 992.12 in Korea. Summarizing, Hayakawa et al. (2015) have mentioned a set of records of auroral candidates in 992 in comparison with contemporary Chinese records of auroral candidates. Stephenson (2015) related the German records in Link (1962) and the Korean record in Goryeosa for this event.

\(^{1}\)Note that Lee et al. (2004) and Stephenson (2015) transcribe the same official history (高麗史) as “Koryosa.” In our article, we transcribe Korean terms based on the Romanization scheme called “Revised Romanization of Korean.”

\(^{2}\)Although Fritz (1873) lacked the date of this event, Short (1749), who is the source for this record, stated its date as 992.01.07.
In this article, we revisit the contemporary original historical records to analyze their description with original texts and correct some misdating that was documented in previous studies. We calculate the magnetic latitude of each potential observational site to estimate the Dst scale, and compare reported dates with the sharp spike in carbon-14 reported by Miyake, Masuda, and Nakamura (2013).

2. Method

In order to reveal the historical evidence of a group of reports of aurora candidates, we restrict this study to the period between 990 and 994 to survey contemporary historical documents all over the world. We introduce and examine relevant historical evidence. The surveyed historical sources and their abbreviations are listed below.3

AQ: Anonymous, Annales Quedlinburgenses, der SLUB Dresden, Mscr. Dresd. Q. 133, Nr. 4. [Manuscript in Latin].
ARE-CE: O’Donovan, J. (ed. and trans.) Annala Rioghachta Eireann: Annals of the kingdom of Ireland by the Four Masters, from the earliest period to the year 1616. Edited from MSS in the Library of the Royal Irish Academy and of Trinity College Dublin with a translation and copious notes, II. 1856. [Critical edition in Old/Middle Irish].
ARE-MS: Brother Michél Ó Cleitrigh, Annaala Rioghachta Eireann, Royal Irish Academy, MS1220. [Manuscript in Old/Middle Irish].
AS: Anonymous, Annalista Saxo, Bibliothèque nationale de France, MS Latin 11851. [Manuscript in Latin].
AU-CE: Hennessy, W. M. and McCarthy, B. (eds.) Annala Uladh: Annals of Ulster otherwise Annala Senait, Annals of Senat: a chronicle of Irish affairs from A.D. 431 to A.D. 1540. I., Dublin, 1887. [Critical edition in Old/Middle Irish].
AU-MS: Cathal Óg McMaghnusa, Annala Uladh, Trinity College Library, MS1282. [Manuscript in Old/Middle Irish].
CT: Kunstanstalt, F. and Brockmann, O. (eds.) Die Dresdner Handschrift der Chronik des Thietmar von Merseburg. 1012–1018; Faksimiledruck, I, 1905. [Manuscript in Latin].
GRS: Jeong Rinji (ed.), Goryeosa (高麗史), Waseda University Library, MS ri06_02809. [Manuscript in Chinese].
TYX: Tiànyuán Yùlì Xiàngyìfù: MS305-257, Naikaku Bunko, Books of Shoheizaka Gakumonjo, in the National Archives of Japan [Manuscript in Chinese].

We show the relevant records in Section 3. We discuss their historical perspectives, the magnetic latitudes of every observational site, and their relevance to the sharp spike of carbon-14 from 993 to 994.

3. Results: Aurora Candidates from 990 to 994

Our survey of aurora records from 990 to 994 brought five records from Saxonian cities in present-day Germany, two records from Ulster on the Island of Ireland, and one record from

3In the following reference of historical documents, we consult mainly the original manuscripts. Where we consult both manuscripts and critical editions, we use abbreviations of -MS for manuscripts and -CE for critical editions.
the Koryo dynasty in the Korean Peninsula. The observational dates are placed on 992.10.21, 992.12.26, and some date between 992.12.27 and 993.01.15. We classify them with respect to their date and observational region. The format of the records is presented as follows: their ID number, their date and place of observation, reference of their original texts, their original texts, and our English translation for them.

3.1. 992.10.21 in Saxonian cities

a) AQ: f. 21b

Original text: DCCCCXCII. ... XII Calend: Novembris totum cœlom ter in nocte visum est rubrum fuisse.

Our translation: 992... On 10.21, the whole sky was seen reddened three times.

b) AS: f. 94b

Original text: Anno dcccxcii, ... Duodecim Kal. Novembris totum cœlum ter in nocte visum est rubrii fuisse.

Our translation: On 10.21, the whole sky was seen reddened three times.

3.2. 992.12.26 in Saxonian cities

a) AQ: f. 22a

Original text: DCCCCXCIII. ... In nocte natalis sancti protomartyris, id est, VII. Calend. Ianuarii, inauditum seculis miraculum vidimus, videlicet circa primum gallicinium tantam lucem subito ex aquilone effulsisse, ut plurimi dicerent diem oriri. Stetit autem u-nam plenam horam, postea rubente aliquantulum cœlo in solitum conversum est col-orem.

Our translation: During the night of St. Protomartyr, i.e. on 12.26, we saw an unheard miracle. Around the first cockcrow, such a light suddenly shone from the North that many people said the Sun had risen. This continued for a whole hour. Afterwards, the sky was slightly reddened and returned to the normal color.

b) CT: f. 58a (see, Figure 1)

Original text: In sequenti anno (992) in gallicantu primo lux ut dies ex aquilone ef-fulsit, & unam sic manens horam, undique celo interim rubente, evanuit.

Our translation: In the following year, at the first cockcrow, a light like the sun rose from the North and this continued for one hour. Everywhere it reddened the sky and then it vanished.

c) AS: f. 95b

Original text: Anno dominii vicarii DCCCCXCIII ... In nocte natalis sancti Stephani in primo gallicantu lux ut dies ex aquilone effulsit, ut plu-rimi dicerent diem oriri. Stetit autem per unam pleniter horam, et postea rubente aliquantulum cœlo, in solitum conversum est colorem.

Our translation: On the night of the birth of St. Stephan, at the first cockcrow, light like the Sun shone from the North and many people said the Sun had risen. This continued for a whole hour. Afterwards, the sky was slightly reddened and returned to the normal color.

Although shortened forms are frequently used in the original manuscripts, we show their original form in the original text given in this paper. For example, while “primo” is frequently given as “pmo.,” we show the former to show their original form.
3.3. 992.12.26 in Ulster

a) AU-MS: f. 53a; AU-CE: p. 500

Original text: Tadbhsiu ingadhaidh feile Stefan, combo croderg in nemh.
Our translation: An unusual appearance on St. Stephan’s Eve, and the sky was blood-red.

b) ARE-MS: f. 388a; ARE-CE: p. 730

Original text: Fordath teineadh do bith for nimh go matain.
Our translation: The fiery hue was seen in the sky till morning.
3.4. 992.12 – 993.1 on the Korean Peninsula

a) GRS: 47, f. 19a (see, Figure 2)

Original text: 成宗...十一年十二月天門開。

Our translation: In 992.12 – 993.01, at night, heaven’s gate opened.

4. Discussion

4.1. Sites and Dates of Observations

In order to determine the date or site of observation for every record, we examine both the original texts and the background of the historical documents in question.

4.1.1. Records 3.1: 992.10.21 in Saxonian Cities

These records were included by Link (1962) and were related to the carbon-14 event in 994 by Stephenson (2015). “Calend” or “Kal.” of the month means the first date of the

5Here, the month is only given as “twelfth month” in the traditional calendar, while the date is not specified.
month in question. When this term is placed with dates like “dd C(K)alendas mm” (in 3.1 a) as “XII Calend: Novembris”), it means “ante diem dd C(K)alendas mm,” i.e. “dd days before the first date in mm month (including the first date)” (Hampson, 1841), thus “XII Calend: Novembris” or “Duodecim Kal. Nov[embris]” means “12 days before the first date in November” in 992, i.e. the date of 10.21 in 992.

The observational sites were not recorded explicitly. However, considering that both AQ and AS were compiled in Saxonian cities, Quedlinburg (N52°47′, E11°09′) and Nienburg (N51°50′, E11°46′), and that the events occurred around their hometowns, we expect that the observational sites were Saxonian cities around Quedlinburg and Nienburg. The descriptions are quite similar to each other except for small differences; hence, the sources may be the same. Considering that AQ was a contemporary source document compiled in the early eleventh century, its text may have been copied into AS, which was compiled around 1148–52. Alternatively, we can assume other contemporary chronicles as the common source, such as the Annales Hersfeldensis or Annales Hildesheimenses maiores (already lost), (Tomaszek, 2010; Dunphy, 2010).

4.1.2. Record 3.2: 992.12.26 in Saxonian Cities

At first sight, these descriptions are similar to each other, and we can expect that they may have the same or a similar origin, as Link (1962) has pointed out. The dates of a) and c) are given as the night of St. Promartyr or St. Stephan, i.e. 12.26, although the date of b) is not written clearly. What is problematic is the year. On one hand, the records a) and c) are placed in the sections of the year 993. On the other hand, the author of record b) places this record “in the following year (in sequenta anno)” of “991 AD (Anno dominicae incarnationis 991)”, i.e. 992. Link (1962) and Stephenson (2015) have therefore mistakenly judged the date as 993.12.26.

However, we must recall the description of the date in the record a): “id est VII. Calend. Ianuarii”. As we stated above, the term of “Calend. Ianuarii” is placed on the first date of January. Thus, the phrase of “VII. Calend. Ianuarii” is read as “ante diem 7 Calendas Ianuarii”, i.e. “7 days before the first date in January (including the first date)” (Hampson, 1841). We should subtract seven days from 993.01.01 to recalculate the exact date, considering that record a) is placed in the first entry of the year 993. We must also note that the beginning of the year was frequently placed on the day of Christmas, December 25, in medieval Germany from the tenth to the fifteenth century after the Carolingian dynasty (Hampson, 1841; Grotefend, 1898). Therefore, the date in question should be placed not on 993.12.26, as in Link (1962) or Stephenson (2015), but on 992.12.26. This can solve the problem of conflicting dates between records a) and c) and record b). The fact that the date given by Calvisius for a quite similar record was 992.12.24 (Calvisius, 1629) supports this solution as well, although he mistakenly places its date on the Christmas Eve, December 24.

The observational sites are regarded as Saxonian cities, just like record 3.1, because AQ, AS, and CT were all compiled at Saxonian cities, that is, at Quedlinburg, Nienburg, and Merseburg (N52°21′, E11°59′). The sources may be the same because the texts are quite similar to each other, even though AQ and CT were compiled in the early eleventh century and during 1012–1018, respectively, and hence are regarded as contemporary records (Warner, 2010; Tomaszek, 2010; Dunphy, 2010).

Here, dd and mm means day and month.
4.1.3. Record 3.3: 992.12.26 in Ulster, Ireland

While record a) of AU is mentioned in Hayakawa et al. (2015), record b) has not previously been mentioned in the context of aurora. The day of St. Stephan is 12.26 (Stokes, 1905). The critical editions and translations of AU (Hennessy and McCarthy, 1887; McAirt and McNiocaill, 1983; CELT, 2000) give its date as “991 alias 992” due to their almanac system. AU places the turn of years up to 1012 not on 1 January, but on 25 March, i.e., the Feast of the Assumption of St. Mary. Thus, McCarthy (1994) claims to place the date of the AU-MS forward by one year. His idea was accepted by McCarthy and Breen (1997) as well. His claim is well confirmed by contemporary records of ARE. The auroral record in ARE is placed in the late section of 992. As the descriptions in AU and ARE are totally different and independent of each other, they are expected to be simultaneous auroral observations by different observers. Considering that ARE places records in chronological order from 1 January to 31 December, we can conclude that the very record of ARE is also placed at the end of 992 and indicates a close relationship with the record of AU.

The observational sites were not recorded explicitly. Their texts are totally different from each other, and hence the original observations were most likely carried out independently. AU was compiled by Cathal Óg McMaghnusa at Belle Isle on Lough Erne, Ulster (N54°16′, W7°33′) in the late fifteenth century (Máille, 1910). ARE was compiled by Brother Micheál Ó Cléirigh from Ballyshannon under the patronage of Fearghal Ó Gadhra at a Franciscan convent of Dunagall (present Donegal; N54°33′ W8°12′) undertaken in 1632 and finished in 1636 (Petrie, 1830). We must note that these annals include excerpts copied from other annals that were previously compiled and lost. Especially the chapters of AU up to the ninth century were written retrospectively in Middle Irish, even though the contemporary language in Ireland is Old Irish (Máille, 1910). The chapter for this event is written in contemporary language, i.e., Middle Irish, and thus copied from contemporary records. In case these chapters were copied from previous sources such as the Chronicle of Ireland, which has been lost, the observational site can be placed at Armagh (N54°21′, W6°39′), Durrow (N52°51′, W72°24′), or Derry (N55°00′, W7°19′) (Flechner, 2013; McCarthy and Breen, 1997; Breeze and Murafle, 2010).

4.1.4. Record 3.4: 992.12–993.01 in Gaeseong, Korean Peninsula

This is the first auroral candidate in Korean historical documents according to Lee et al. (2004). Stephenson (2015) indicates the relationship of this record with the sharp spike of carbon-14 in 994. Its date is placed in the twelfth month in the eleventh year of Seongjong (承宗), i.e. the period between 992.12.27 and 993.01.15 (An, Sim, and Song, 2009).

This record was categorized into a chapter for unusual phenomena on stars including records of red vapor (赤氣) or white vapor (白氣) in the astronomical treatise (天文志) of Goryeosa (高麗史). Although the expression “heaven’s gate opened (天門開)” is not so popular for aurore records in East Asian histories, Hayakawa et al. (2016e) examined records including this term to show that they can indicate auroral candidates. The very expression with a similar meaning “heaven’s split (天裂)” is frequently found in Goryeosa. Similar terminology is used for the first auroral candidate in China in BCE 193 that states “heaven’s open (天開)” (Hànshū, Astronomy VI: p. 1710; Saito and Ozawa, 1992; Yau, Stephenson, and Willis, 1995; Hayakawa et al., 2016e), and we can find illustrations for this term in Chinese manuals for astronomical divinations (see Figure 3). We have a Japanese record on 1770.09.17 reporting “heaven’s split (天裂)” observed in both
Figure 3 “Heaven’s Split” in Tiānyuán Yǔlì Xiángyìfù, a Chinese manual of astronomical divination (stored in the National Archive of Japan, v. I, f. 8a).

Edo and Kanazawa (Hayakawa et al., 2016e), which is contemporary with simultaneous observations of auroras on the same date in China (Willis, Stephenson, and Singh, 1996; Kawamura et al., 2016).

We can assume this was observed at Gaeseong (N37°58’, E126°33’), considering the East Asian tradition to locate observatories near the capital city to report astronomical phenomena to the emperors as soon as possible (Keimatsu, 1970; Hayakawa et al., 2015).

4.2. Geomagnetic Latitudes of Observational Sites

Hayakawa et al. (2015) showed records of auroral candidates in ancient Chinese chronicles in 960–1279, covering the age of the sharp strike of carbon-14 in 994. In this era, the

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7See, section of Meiwa seventh year, seventh month, date 28, in MS 16.28-11-11, Kanazawa City Library.
geomagnetic latitude of East Asia was higher than at present (Butler, 1992; Kataoka et al., 2016). Therefore, it was easier to observe the aurora in East Asia (Hayakawa et al., 2015), and a little more difficult to observe it in Europe.

The geomagnetic latitude of observational sites of auroras indicates the relative scale of magnetic storms because the equatorward boundary of the auroral oval is correlated with the Dst index (Yokoyama, Kamide, and Miyaoka, 1998). The event of 992.10.21 was recorded in Saxonian cities. In the event of 992.12.26, the observation of an aurora was recorded simultaneously in Ulster and Saxonian cities. Shortly after this event, a Korean record in GRS follows these records on some date or dates between 992.12.27 to 993.01.15.

Using the global geomagnetic field model CAL3k.4b (Korte and Constable, 2011), we compute the geomagnetic latitude of observational sites in 992–993 and obtain values of approximately 48° for Saxonian cities, 49° for Ulster, and 35° for Gaeseong. We note that the annals in Ulster and Saxonian cities involve the records of nearby areas as stated above. Therefore, an uncertainty of approximately 2° remains as well as the uncertainty of the model. The equatorward boundary of the auroral oval shows a good correlation with the Dst index (Yokoyama, Kamide, and Miyaoka, 1998). The Dst index is a proxy for the strength of the large-scale electric current, called the ring current, that surrounds the Earth. The prime driver to intensify the ring current is large-scale magnetospheric convection. Hot ions and electrons originating in the plasma sheet on the night side are transported toward Earth by convection. As they drift earthward due to the convection, the hot ions and electrons gain kinetic energy, and their pressure increases. Because of the spatial difference in the number of ions and electrons, the ring current forms (Ebihara and Ejiri, 2000). Furthermore, as the electrons are convected deep into the magnetosphere, they are adiabatically compressed and the electron temperature anisotropy leads to an instability that causes the growth of electromagnetic waves (Kennel and Petschek, 1966; Tsurutani and Lakhina, 1997). The waves scatter the electrons so that they precipitate from the magnetosphere into the upper atmosphere, resulting in aurora. Thus, it is reasonable to consider that the equatorward boundary of the auroral oval is correlated with the earthward boundary of the plasma sheet and the Dst index. Yokoyama, Kamide, and Miyaoka (1998) suggested an empirical formula to relate the equatorward boundary of the auroral oval and the Dst index. Assuming that the equatorward boundary of the auroral oval was located at Gaeseong (35° magnetic latitude), we estimate the Dst index to be −970 nT. The minimum value of the Dst index that has been officially published by the World Data Center, Kyoto, since 1957 is −589 nT, which was recorded on March 14, 1989. Although the estimated Dst is a crude approximation and a careful diagnosis is necessary, there is a possibility that the magnetic storm that occurred in the period between 992.12.27 and 993.01.15 was a stronger storm than any of the storms recorded since 1957.

The magnitude of the magnetic storm is probably not as extreme as that of the Carrington event in terms of the equatorward boundary of the auroral oval. The equatorward boundaries of the auroral observation during the Carrington event were 23° in magnetic latitude, in both the North and South hemispheres (Kimball, 1960; Hayakawa et al., 2016b), and hence its Dst value for this event was estimated by Tsurutani et al. (2003) to be −1760 nT. Uncertainty in estimating the magnitude of the magnetic storm(s) comes from the lack of world-wide historical records of observation, especially in low-latitude regions. This may be improved if additional records are discovered. The abnormality of the magnetic storms around the 990s might be explained not by a single extreme magnetic storm, but by several strong magnetic storms, as we discuss below.
4.3. Long-term Solar Activity

Hayakawa et al. (2015) showed records of auroral candidates in medieval Chinese official histories spanning 960 – 1279, including the time of the event considered here, in 994. Figure 3 of Hayakawa et al. (2015) showed the peak of the number of auroral candidate observation after the 994 carbon-14 peak (Miyake, Masuda, and Nakamura, 2013), before the Oort minimum (1010 – 1050). The records of auroral observation in the 990s suggest intense solar activity during the period just before the Oort minimum. We must at the same time consider that Chinese official histories, which had continuous and systematic observations in this age, did not record auroral observations between 988 and 996 (Hayakawa et al., 2015; Stephenson, 2015). We expect that the aurora was simply not observed in this period in China or was not seen due to weather conditions. Alternatively, even if the aurora was observed in this age, it may have been missed in the process of editing official histories from original observational records. The concentration of records of auroral observations may support the occurrence of intense solar activity in these periods, although the relationship with the sharp spike of carbon-14 in 994 is still questionable.

4.4. Clustering Observations of Auroras in this Era

One of the features in the records of aurora observations from 992 – 993 is that we find clustering in the records from 992.12.26 to the period between 992.12.27 and 993.01.15 (Records 3.2, 3.3, and 3.4). Large flare-productive active regions often generate multiple flares and coronal mass ejections (CMEs), resulting in prolonged space weather disturbances and auroral activities. The Carrington event in 1859 caused a series of auroras lasting as long as eight days from 08.28 to 09.04 (Loomis, 1859, 1860a, 1860b, 1860c, 1860d, 1861a, 1861b, 1865). The auroral observations in 1770.09 provide the earliest known conjugate sighting lasting at least three days from 09.16 to 09.18 (Willis, Stephenson, and Singh, 1996; Kawamura et al., 2016). As shown in Tsurutani et al. (2008), the extreme events such as the one in 1972.08 and the Halloween event in 2003.10 are caused by a series of CMEs from a single active region (Mannucci et al., 2005; Tsurutani et al., 2007; Shiota and Kataoka, 2016). Kataoka et al. (2016) discussed prolonged auroral activity based on historical documents in East Asia and modern observation. A total of 6 events out of the 20 largest magnetic storms (with a Dst index of < – 250 nT) in Solar Cycles 22 (1986 – 1996) and 23 (1996 – 2003) occurred multiply within a week (Kataoka et al., 2016), just like the Halloween event, which featured the clustering of CMEs in October to November 2003 (Mannucci et al., 2005; Tsurutani et al., 2007; Shiota and Kataoka, 2016). Therefore, the auroral observations in late 992 may be regarded as prolonged auroral activity, indicating severe clustering of CMEs in this period.

One may also speculate that the series of CMEs from 992.10 to 993.01 was produced by a single active region. As shown in Tsurutani et al. (2008), the extreme events with clustering of CMEs such as the event on 1972.08 with the highest solar wind speed in observational history (Vaisberg and Zastenker, 1976), the above-mentioned Halloween event on 2003.10 with clustered observations of CMEs (Mannucci et al., 2005; Tsurutani et al., 2007), and the Carrington event in 1859 (Carrington, 1859, 1863; Tsurutani et al., 2003) are related with a single active region. It is known that the lifetime of a sunspot \( T \) is proportional to the sunspot area \( A \): \( T \approx A/10 \), where \( T \) is in days and \( A \) is in millionths-of-a-hemisphere (mhs) (the Gnevyshev–Waldeimeyer law; Gnevyshev, 1938; Waldmeier, 1955; Petrovay and van Driel-Gesztelyi, 1997). According to Notsu et al. (2013), the area of the starspots in the superflare stars ranges from a few thousands of mhs, namely comparable to the largest
known sunspots, to as large as $10^5$ mhs. If the lifetime of such a huge spot follows the same scaling, the spot should survive months and even years, and may continuously produce flares and CMEs during a significant part of its life. However, the auroral records do not strongly support the recurrence of events with solar rotations. We have not found records of naked-eye sunspots to support the long-lasting intense solar activity reported here.

4.5. Relationships with a Sharp Spike of Carbon-14 in 994

Comparison between the records of auroral observations and the sharp spike of carbon-14 in 994 recorded in tree rings (Miyake, Masuda, and Nakamura, 2013; Miyake et al., 2014) is intriguing. The time lag between carbon-14 input and the absorption by trees has been estimated using the box model of the carbon cycle (see e.g. Appendix in Güttler et al., 2015). Güttler et al. (2015) discussed the timing of the carbon-14 production that caused the peak of carbon-14 in tree rings in 775 by using a carbon cycle box model as well as the tree-ring records from the northern and southern hemispheres. They suggest that the event had occurred around March 775, with an uncertainty of six months.

According to the case study of the 775 event by Güttler et al. (2015), the time lag between the generation of carbon-14 in the atmosphere and the response of isotope ratio in tree rings is several months. Applying the same timescale to the 994 event, under the assumption that the atmospheric circulation is not greatly changed, it is suggested that the timing of the event that yielded the carbon-14 spike in 994 should have occurred sometime in late-993 to mid-994. In other words, if the 992.12.26 auroral event was associated with an extremely strong cosmic ray flux, it should be reflected as the increase in carbon-14 in 993 as well. We note that such an enhancement in 993 is not seen in the carbon-14 data in Japanese trees surveyed by Miyake, Masuda, and Nakamura (2013) and Miyake et al. (2014), but a search for the signature of increased carbon-14 in 993 from other trees, especially those from the southern hemisphere, deserves to be made to further the discussion on the relationship between the carbon-14 spike in 994 and the historical records of auroras in late 992 to 993.

5. Conclusion

We investigate contemporary auroral records during 990–994. There are five records from Saxonian cities in Germany, two from Ulster in Ireland, and one from the Korean Peninsula. These records cluster from late 992 to early 993, i.e. on 992.10.21, 992.12.26, and some date(s) between 992.12.27 and 993.01.15, and show the strong solar activity in at least 992–993 (just before the Oort minimum). The estimated Dst index is $-970$ nT, suggesting that the storm was more extreme than any of the storms formally recorded since 1957 (e.g. Mannucci et al., 2005; Tsurutani et al., 2007). The timing of the events is compared with the sharp spikes in carbon-14 shown by Miyake, Masuda, and Nakamura (2013). However, the relation is not obvious. We encourage further surveys of records of low-latitude auroras and tree-rings in the southern hemisphere in the early 990s.

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Note that GRS only shows us the month in the traditional calendar (the twelfth month) and does not specify the date of observation, while other records for aurora-like events are given with the exact date.
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