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A candidate auroral report in the *Bamboo Annals*, indicating a possible extreme space weather event in the early 10th century BCE

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Abstract

Historical auroral reports extend our knowledge of solar eruptions and long-term solar variability in the millennial time scale beyond the chronological coverage of instrumental observations, in the decadal to centennial time scales. Such chronological extensions benefit the scientific community, increasing the number of case studies on extreme space weather events with lower frequency but higher potential impact on modern technological infrastructure. So far, the earliest known datable reports of candidate aurorae have reached back to the 7th century BCE. Beyond this time series, we have analysed a celestial report in the Chinese *Bamboo Annals* that has attracted little scientific interest, probably owing to the controversial interpretations for the physical identity and the chronology of the event. Our philological analysis establishes its probable auroral nature. The textual description can be compared with early modern accounts of visual auroral observations for the multi-colour aurorae. We have located the observational site around Hàojīng (N34°14′, E108°46′) and dated the event to 977 ± 1 or 957 ± 1 BCE. On this basis, we have computed the equatorward extension of the auroral visibility as $\leq 39.0°$ in magnetic latitude and reconstructed the equatorward boundary of the auroral oval as $\leq 45.5°$ in invariant latitude. Our investigations empirically associate this candidate aurora with an extreme geomagnetic storm. We have compared this space weather event with proxy-based reconstructions of long-term solar variability and characterised it as a unique space-weather reference before the Neo-Assyrian Grand Minimum (alternatively Homeric Grand Minimum) in *ca*. 810 – 720 BCE.

Keywords: Sun: activity; Sun: coronal mass ejections (CMEs); Solar-terrestrial relations; Planets and satellites: aurorae; Planets and satellites: magnetic fields; History and philosophy of astronomy

1. Introduction

It is known that, significant geomagnetic storms often extend auroral visibility towards the mid- to low-latitude regions. This happens when solar eruptions launch sufficiently large and fast interplanetary coronal mass ejections (ICMEs) with geo-effective interplanetary magnetic field (Gonzalez et al., 1994; Daglis et al., 1999; Daglis, 2006; Liu et al., 2019). Recent examples are the extreme space weather events of March 1989 and September 1859, when large sunspot active regions launched a number of interplanetary coronal mass ejections, caused geomagnetic superstorms, and extended auroral visibility down to tropical regions such as the Caribbean coast (Allen et al. 1989;

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Tsurutani et al. 2003; Green & Boardsen 2006; Silverman 2006a; Cliver & Dietrich 2013; Hayakawa et al. 2019a; Boteler 2019). The analyses of such extreme space weather events are not just of specific scientific interest but also of broader public concern, as these events seriously affect the technological infrastructure on which our civilisation increasingly relies (Lanzerotti 2017; Baker et al. 2018; Riley et al. 2018).

Historical records of datable visual aurorae improve our understanding of the past solar-terrestrial environment (Silverman 1992, 1998; Vaquero & Vázquez 2009). Their spatial evolution has provided key references for extreme space weather events preceding the onset of systematic geomagnetic measurements in the mid-19th century (Willis & Stephenson 2000, 2001; Willis et al. 2005; Vaquero & Trigo 2005; Silverman 2006b; Vázquez & Vaquero 2010; Hayakawa et al. 2017a, 2017b; Hattori, Hayakawa & Ebihara 2019; Stephenson et al. 2019; Bertolin, Domínguez-Castro & de Ferri 2020; Carrasco & Vaquero 2020). Their temporal variability has been analysed to visualise the space climate on centennial time scales (Siscoe 1980; Silverman 1992; Nevanlinna 1995; Usoskin et al. 2013; Lockwood & Barnard 2015; Vázquez et al. 2016; Wang et al. 2021) and emphasize peculiarities of the Maunder Minimum and the Dalton Minimum (Vaquero et al. 2010; Usoskin et al. 2015; Vaquero & Trigo 2015; Riley et al. 2015; Domínguez-Castro et al. 2016; Hayakawa et al. 2021; Silverman & Hayakawa 2021).

Recently, datable records of candidate aurorae in historical sources have been identified as far back as the first millennium BCE (e.g., Silverman 1998, 2006b; Stephenson et al. 2004; Vaquero & Vázquez 2009; Wang et al. 2021). On current knowledge, the earliest known textual reports were composed in the Assyrian Empire from 679 to 655 BCE, while the earliest known graphical record is in a Syriac chronicle of the 8th century CE (Silverman 1998, 2006b; Stephenson, Willis & Hallinan 2004; Hayakawa et al. 2017a, 2019b). It is intriguing to extend our investigations even further back in time. The Chinese have a long-running tradition of celestial observations (Xu, Pankenier & Jiang 2000; Pankenier 2013). Recently, van der Sluijs (2021, pp. 36 – 38) has drawn attention to a possible earlier auroral account in the Chinese *Bamboo Annals* (竹書紀年: *Zhúshū Jìnián*). Although several other early celestial reports were obtained from this account and studied in different astronomical contexts (e.g., Pang et al., 1986; Stephenson 1992; Pankenier 2013), the record in question has so far garnered little interest (Xu et al. 2000). This is partly because – in the same modern publication — this record has been interpreted on one hand as a candidate auroral account of the 10th century BCE (Xu et al. 2000, pp. 188 and 358) and on the other hand as a cometary account for 1034 BCE or 959 BCE (Xu et al. 2000, pp. 110 and 319). In this study, we analyse the original sources to resolve their philological and chronological discrepancies and identify the observational site. We further compare these source records with early modern visual accounts to support the auroral interpretation; estimate the equatorward extension of the auroral oval combining the source records and the archaeomagnetic field model; and contextualise this report within the long-term solar activity.

2. Philological analysis

This celestial report has been conflictingly interpreted in Xu et al. (2000) based on two different series of textual variants of the *Bamboo Annals*. Fig. 1 (a) shows the pertinent folio of the Current Text (CT: 今本, *jīnběn*) (v. 2, f. 8b), which was printed in the 16th century CE. Fig. 1 (b) and (c) illustrate the corresponding excerpts in the works *Tàipíng Yùlǎn*, of the 10th century CE (TY: 太平御覽, v. 874, f. 4b), and *Gǔjīn Túshū Jíchéng* (GTJ: 古今圖書集成, v. 102, f. 2a), of 1726 CE. It is from the latter two accounts that modern scholars reconstructed the Ancient Text (古本, *gǔběn*) of the *Bamboo Annals* in critical philological editions (Fang & Wang 1981, p. 44; Fang 2011, p. 30). These records report mostly the same content with slight variations; as modified from Xu et al.'s translations (Xu et al. 2000, pp. 110 and 188):

(Current Text) In the 19th year [of King Zhāo]: In spring, there was a fuzzy star in Zǐwēi. [Fig. 1 (a)]

(Ancient Text) In the last year of King Zhāo of Zhōu: during the night[1], a five-coloured light penetrated Zǐwēi. In this year, the King inspected the southern regions and did not return.

These variants both describe a certain celestial phenomenon in the late reign of King Zhāo (昭王) of the Zhōu (周) Dynasty, which penetrated or was located in the Zǐwēi (紫微) region in the sky. The phenomenon itself was variously described as a 'fuzzy star' (星孛: *xīngbèi*) and a 'five-coloured light' (五色光: *wǔsèguāng*), while the dating was either the spring of Zhāo's 19th year or a date in his last year. This variation has resulted in the contradictory interpretations of this phenomenon as a comet in 1034 or 959 BCE (Xu et al. 2000, pp. 188 and 358) and an aurora in 950 BCE (Xu et al. 2000, pp. 188 and 358).

In order to assess the relative merits of these variant readings, it is necessary to examine the philological background of the source documents more closely. In doing so, we follow the explanations given in previous philological studies (Nivison 1993; Shaughnessy 2006, pp. 185 – 256; Knechtges & Chang 2014, pp. 2342–2348). According to these publications, the *Bamboo Annals*, starting from the Xià Dynasty (夏), were probably compiled originally in the Wèi (魏) Kingdom by the early 3rd century BCE and were recovered from a nobleman's tomb at Jí (汲) around 279 – 281 CE as a series of bamboo slips. This manuscript was then subjected to transcriptions and editing from the Western Jìn Dynasty (西晋: 265 – 316 CE) onward and was probably lost in its original form by — or at most dur-

[1] Here, we have followed correction of *qīng* (清) to *yǒu* (有), in Fang & Wang (1981, p. 44).

Fig. 1. Variant fragments of the *Bamboo Annals*. Panel (a) shows an excerpt from the Current Text (CT) of the *Bamboo Annals* (v. 2, f. 8b; MS B1452800 in © Institute for Advanced Studies on Asia of the University of Tokyo). Panels (b) and (c) show excerpts from the Ancient Text (AT) of the *Bamboo Annals*, cited in (b) *Tàipíng Yùlǎn* (太平御覽, v. 874, f. 4b; MS Nu-3 in © the National Diet Library of Japan) and c) *Gǔjīn Túshū Jíchéng* (古今圖書集成, v. 102, f. 2a; Chen & Jian 1934, f. 50b).

ing — the Sòng Dynasty (宋: 960 – 1279 CE). Long afterward, in the 16th century, a different edition of the *Bamboo Annals* was printed at Tiānyī Gé (天一閣) in Níngbō (寧波) (see Fig. 1 (a)), starting the chronology from as early as the Yellow Emperor (黃帝). It is this version and its close variant(s) that have been known as the Current Text. Their authenticity has remained controversial owing to possible fabrications during the Míng Dynasty (明: 1368 – 1644) (e.g., Keightley 1978; Shaughnessy 2006). In contrast, the Ancient Text is a recent scholarly reconstruction on the basis of excerpts and citations in extant printed documents predating the Míng text (e.g., Fig. 1 (b) and (c)); updated several times, the most recent critical editions include Fang & Wang (1981) and Fang (2011).

As the authenticity of the Current Text is questionable on account of its heavy editing or even its possible fabrication, it is advisable to rely on the Ancient Text for the celestial report at hand. Therefore, we regard the reported celestial phenomenon not as a 'fuzzy star' but as a 'five-coloured light', and give less credence to the seasonal specification uniquely found in the Current Text. Thus, the conflicting identification in Xu et al. (2000) is resolved in favour of the reading that they interpreted as an aurora as opposed to the cometary one.

With some alteration, similar records for this event in the late reign of King Zhāo are found in some more Chinese accounts compiled centuries after the rediscovery of the *Bamboo Annals*, notably in Tánmózuì's excerpt and *Zīzhì Tōngjiàn Wàijì* (資治通鑑外紀, v. 3, f. 18b), but these do not explicitly name their source as the *Bamboo Annals*. While we consider the description of the Ancient Text to be more reliable because of its temporal proximity to the event itself, the relationship with these other sources is worth further investigation in future studies (*c.f.* Lee 1969, p. 22; Zürcher 2007, p. 273; van der Sluijs 2021, pp. 36 – 38).

3. Scientific interpretation and early modern parallels

The Ancient Text gave the observation time as 'during the night', the appearance as 'five-coloured', and the direction as 'Zǐwēi'. Zǐwēi is the circumpolar region (appendix I of Ho 2003). The description thus locates this celestial phenomenon in the northern sky. The explicit mention of nighttime observation rules out daytime manifestations of atmospheric optics, which sometimes mimic candidate aurorae (Usoskin et al. 2017). The colouration indicates a mixture of multiple colours, which was expressed through the traditional Chinese notion of five colours associated with the five elements: red, white, blue/green, black, and yellow (e.g., Table 3.2 of Wang 2006; see also Pankenier 2013).

The occurrence of a multicoloured phenomenon in the northern sky during the nighttime is consistent with visual auroral displays in mid-latitude regions. In selecting appropriate parallels from the literature, it is again important to filter out cases that can be explained by atmospheric optics, in this case such as the nighttime manifestations. Lunar coronae or aureoles have colours easily discernible to the human eye, but necessarily form around the moon. Lunar haloes, too, are centred on the moon, but have far fainter colouration (Minnaert 1993, pp. 208 – 232). Confusion with the aurora is most likely for the case of an auroral arc, historical reports of which could resemble descriptions of moonbows. Appearing on the opposite side of the sky to a full moon, moonbows may be seen in the northern sky, but only do so a few hours before sunrise or after sunset and – unlike this celestial phenomenon examined here – appear colourless (Minnaert 1993, pp. 207 – 208).

Taking such considerations into account, we have located a number of unambiguously auroral reports similar to the one from the *Bamboo Annals*. Several of the low-latitude aurorae identified in Chinese and Korean records from 500 to 1770 CE exhibited multiple colours (Abbott and Juhl, 2016; Hayakawa et al. 2015, 2017c); their rarity may indicate a significant intensity of the precipitating electrons and a significant brightness of the reported candidate aurorae (Abbott and Juhl, 2016; Ebihara et al., 2017). Striking parallels are also found in quite a few Western accounts of mid-latitude aurorae from the 18th to early 20th centuries. For example, Isaac Greenwood (1731, p. 57, emphasis added) remarked as follows on the chromatic pattern of the great aurora of 1730 October 22, which he observed from New England, presumably Cambridge, Massachusetts (N42°22′, W071°06′):

'But the most intense *Red* was towards the N W. and N E. by E. between which were various pyramidical Streams of different Colours, some *Blue*, some *Green*, others *Flame–coloured*, &c. many tinctured with, and all terminated by the diffusive *Rosiness*. One Stria was of a surprising Lustre, of a light *Azure* turned upon *Green*, appearing N W. by N.'

Stationed near Cambridge, England (N52°12′, E000° 07′), Morgan & Barber (1848, p. 4, emphasis added) offered the following impression of the intense geomagnetic storm of 1847 October 24:

'. . . a crown was formed near the magnetic zenith, from which all the rays appeared to diverge; their colours were most splendid and of peculiar transparency, especially the *red* and *green*, the former being quite like *carmine*, and the latter that of the *pale emerald*; the central part of this canopy, or that near the magnetic North, was of a very *yellow* colour, one streamer being quite like *gold* . . .'

Similarly, on 1859 August 29/30, a display of the *aurora australis* with blue, green, yellow, and red colouration was reported from Cape Otway (S30°51′, E143°50′): 'Aurora most magnificent at 6 ^{h} 30 ^{m} P. M. and continued visible until after 2 A. M., displaying itself in the form of a rainbow, the arc extending to about 60° or 70°. First color above the horizon a light *blue* with a tint of *green*, blending into second, a very light *yellow*, again blending into third, a deep *red*' (Loomis 1861, p. 78, emphasis added). Days later, on 1859 September 1/2, northern lights were observed with '*every color of the rainbow except blue*' at Jefferson County, Mississippi (N31°50′, W091°). The report reads:

'A belt of *white* light tinged with *pink* shot up from the northern horizon to the height of twenty or twenty-five degrees and extended east and west nearly the same elevation. . . . It presented *every color of the rainbow except blue*. At the same time a *brownish red* column shot up from the N. E. resembling the flame of a huge lamp or candle, vibrating and flickering as though disturbed by wind.' (Loomis 1859, pp. 402 – 403, emphasis added)

On the same night, an auroral display was reported from Havana (N23°08′, W082°21′) with white, red and blue colours: 'The upper red segment rose considerably above *Polaris*. The illumination faded towards the northwest and embraced the whole of the auroral base; afterwards it rose again to the height of 12°. *White* rays with *red* and *blue* were then seen towards the west, which dilated longitudinally, oscillated laterally, were extinguished and resumed their brilliancy again by turns' (Loomis 1859, p. 404, emphasis added). Further, the spectroscopist and solicitor John Rand Capron, based in Guildford, England (N51°14′, W000°, 34′), witnessed an auroral corona in varied colours on the evening of 1870 October 24:

'Two patches of intense *crimson* light about this time massed themselves on the north-east and north-west horizon, the sky between having a bright *silver* glow. The *crimson* masses became more attenuated as they mounted upwards; and from them there suddenly ran up bars or streamers of *crimson* and *gold* light, which, as they rose, curved towards each other in the north, and, ultimately meeting, formed a glorious arch of *coloured* light, having at its apex an oval *white* luminous corona or cloud of similar character to the phosphorescent clouds previously described, but brighter. At this time the spectator appeared to be looking at the one side of a cage composed of glowing *red* and *gold* bars, which extended from the distant parts of the horizon to a point over his head.' (Capron 1879, p. 18, emphasis added)

The well-known great aurora of 1921 May 14/15 appeared as follows to an observer in Broadway, Manhattan (N40°47′, W073°58′): 'The flashes extended from the north to the zenith, and a bright star overhead was dimmed by rays of flickering light that showed *all colors of the rainbow*.' (*The New York Times*, 1921 May 15, cited in Silverman & Cliver 2001, p. 527, emphasis added). Herbert L. Choate, who was an observer of the same auroral event based in Drexel, Nebraska (N41°42′, W96°022′), was equally struck by the varied colours: 'At 9:40p. m. the entire sky, except a thin strip along the southern horizon, was covered with intermingling masses of light. The predominating color was *yellow*, but splashes of *red*, *orange*, and *green* tints appeared at intervals in different parts of the sky.' (Lyman 1921, p. 407, emphasis added).

4. Date and site

The Ancient Text dated the event discussed here to the 'last year of King Zhāo (昭王末年)', coinciding with the southern expedition from which he did not return (Fig. 1 (a)), while the Current Text dated it to the 'spring' of 'the 19th year' of this king (Fig. 1 (b)). Chinese chronology before the 9th century BCE remains somewhat unsettled. King Zhāo's reign has been variously located in 977/975 – 957 BCE in Shaughnessy's chronology (Shaughnessy 1999, pp. 322 – 323; 2006, p. 185) and in 995 – 977 BCE in the Xià-Shāng-Zhōu Chronology Project (XSZ Chronology Project Group 2000, p. 88; Li 2002). According to these two chronologies, we date this event to either 977 ± 1 or 957 ± 1 BCE (see also Shaughnessy 1999, pp. 322 – 323), accommodating conversion uncertainty from the ancient calendar system to the Julian calendar.

The Current Text uniquely specifies the season as 'spring'. If this were truly the case, this event would have been chronologically limited to the first three months of the year in the traditional calendar (Wilkinson 2000, p. 171). However this seasonal description does not appear in the Ancient Text and thus lacks credibility (e.g., Keightley 1978; Shaughnessy 2006). Therefore, it is probably sensible to stay away from narrowing down its date beyond its observational year: 977 ± 1 BCE or 957 ± 1 BCE.

It is slightly challenging to identify the exact observational site from the existing texts. The Ancient Text briefly reported the five-coloured light and continued with King Zhāo's inspection of the southern region, which was probably the Chǔ (楚) region (Fig. 1 (a); Fang 2011, p. 30; see also Shaughnessy 1999, pp. 322-323). It does not specify whether the celestial phenomenon was observed at the capital or somewhere south of it. As such, it will be safest to assume the northernmost option – the capital. The Zhōu capital was at Hàojīng (鎬京: N34°14′, E108°46′) from King Wǔ's conquest to Quǎn Róng's invasion in 771 BCE, including King Zhāo's entire reign (Rawson 1999, pp. 390 – 397). Therefore, we consider that the five-coloured light was visible down to Hàojīng, if not further southward.

5. Equatorward extension of the auroral oval

On the basis of the reported details and discussions in Sections 3 and 4, it is possible to conservatively compute the equatorward boundaries of the auroral *visibility* and auroral *oval* (Fig. 2 of Hayakawa et al. 2018), and estimate the magnitude of the causative geomagnetic storm. Following Section 4, we have computed the magnetic coordinates of the observational site Hàojīng in 977 ± 1 BCE and 957 ± 1 BCE. The archaeomagnetic field model Cals3k4b locates the north geomagnetic pole at N84°38′ E083°06′ in 977 BCE and N84°43′ E081°08′ in 957 BCE (Korte & Constable 2011), respectively. On this basis, we have computed the geomagnetic coordinates of Hàojīng as 39.0° MLAT 27.4° MLON in 977 BCE and 38.9° MLAT 29.5° MLON in 957 BCE, respectively. This indicates that Hàojīng at that time was located ≈ 15° closer to the north geomagnetic pole than in the modern time (24.5° MLAT in 2014) and had much more opportunity to witness auroral

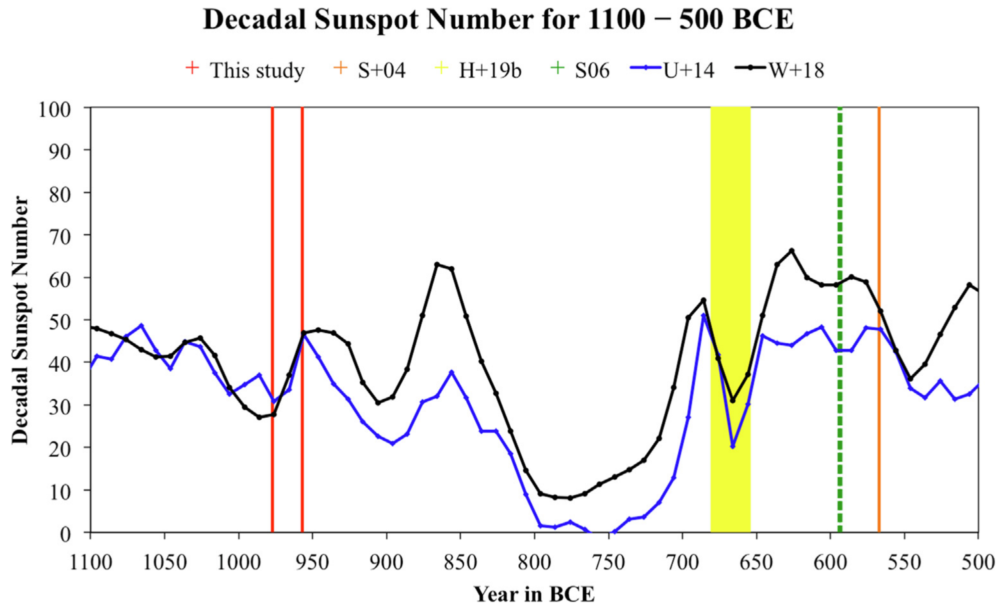

Fig. 2. The earliest known candidate auroral records contextualised relative to the reconstructed sunspot number. The red vertical lines show the plausible dates of the candidate auroral record in the *Bamboo Annals* (977 BCE and 957 BCE) in this study. The yellow shade, the orange vertical line, and the green broken vertical lines show the date range of the candidate aurorae in the *Assyrian Astrological Reports* (Hayakawa et al. 2019b, abbreviated as H + 19b), the date of an entry in the Astronomical Diaries from Babylon (Stephenson et al. 2004, abbreviated as S +04), and Ezekiel's vision (Silverman 2006b, abbreviated as S06) with corrected dates and reliability caveats (Hayakawa et al. 2019b). The blue and black curves represent the decadal sunspot number reconstructed from the cosmogenic isotopes in Usoskin et al. (2014), abbreviated as U+14, and Wu et al. (2018), abbreviated as W + 18.

displays (see also fig. 5 of Korte & Stolze 2016), as the north geomagnetic pole was inclined toward the Siberian side in comparison with its modern inclination to the northern side of Greenland (N80°15′ W072°32′ in 2014), according to the IGRF-12 model (Thébault et al. 2015).

The five-coloured light reportedly penetrated the region Zǐwēi. We therefore assumed the auroral elevation to be $\geq 34°$, namely above the celestial pole. This allowed us to geometrically derive the equatorward boundary of footprints of the magnetic field lines along which the auroral electrons precipitated. This is calculated using invariant latitudes (ILATs), defined as the magnetic coordinates at which the magnetic field lines intersect the equatorial plane (O'Brien et al., 1962; McIlwain, 1966), as visualised in Fig. 2 of Hayakawa et al. (2018). Specifically, the ILAT Λ is defined by the equation $\cos^2\Lambda = 1/L$. The L-value is related to the second adiabatic invariant of trapped particles, and is almost constant along field lines within 1% (McIlwain, 1961). Since it depends on the magnetic field, we need a reliable magnetic field model to calculate it. In order to evaluate the equatorward boundary of the auroral oval (EBAO) on the basis of a unified and reliable standard, we used the dipole magnetic field (Korte and Constable, 2011). In the latter, the ILAT is given by the angle from the direction of the north magnetic pole minus 90° (McIlwain, 1966).

We reconstructed the equatorward boundary of the auroral oval as $\leq 45.5°$ (977 BCE) and $\leq 45.4°$ (957 BCE), respectively. For these occasions, the empirical correlation between the equatorward boundary and storm intensity (Yokoyama, Kamide & Miyaoka 1998) indicates an intensity of minimum Dst estimate $\leq -296 \pm 47$ nT (977 BCE) and $\leq -300 \pm 48$ nT (957 BCE), respectively. These error margins enable us to set the effective least negative magnitude at ≤ -249 nT and most certainly categorise this storm as an extreme geomagnetic storm (Dst ≤ -250 nT). Within the standard Dst index, geomagnetic storms of similar magnitude have been recorded 39 times since the International Geophysical Year (1957–1958), as shown in Table 1 (see also: Meng, Tsurutani & Mannucci, 2019). Here, the extreme geomagnetic storms especially in 1957 – 1959 and 1989 widely extended the auroral visibility to the lower MLAT regions (Allen et al., 1989; Vallance Jones, 1992; Silverman, 2006; Boteler, 2019; Hayakawa et al., 2022). Similar space weather events were also reported on 1938 January 21/22 and 25/26, when the equatorward boundary extended down to 40.3° ILAT and 40.3° ILAT for extreme geomagnetic storms of minimum Dcx = −328 nT and −336 nT (Hayakawa et al. 2021).

6. Summary and discussions

In this article, we have analysed an early celestial report in the Chinese *Bamboo Annals*, which had generated contradictory dating and interpretations even in a single study (Xu et al. 2000) and hence attracted little attention in the scientific community. The conflicting interpretations were derived from text variants in the Ancient Text and Current Text, which reported a 'five-coloured light' and a 'fuzzy

Table 1
Extreme geomagnetic storms (minimum Dst ≤ -250 nT) from the International Geophysical Year to the present (1957 – 2021). Their intensities have been visualised with the most negative Dst index, as derived from the WDC for Geomagnetism at Kyoto (WDC Kyoto et al., 2015; see also: Meng et al., 2019). Shown are their date, minimum Dst (min. Dst) and Solar Cycle.

Year	Month	Date	min. Dst (nT)	Solar Cycle
1957	01	21	−250	19
1957	03	02	−255	19
1957	09	05	−324	19
1957	09	13	−427	19
1957	09	23	−303	19
1958	02	11	−426	19
1958	07	08	−330	19
1958	09	04	−302	19
1959	07	15	−429	19
1960	04	01	−327	19
1960	04	30	−325	19
1960	10	07	−287	19
1960	11	13	−339	19
1961	10	28	−272	19
1967	05	26	−387	20
1970	03	08	−284	20
1981	04	13	−311	21
1982	07	14	−325	21
1982	09	06	−289	21
1986	02	09	−307	21
1989	03	14	−589	22
1989	09	19	−255	22
1989	10	21	−268	22
1989	11	17	−266	22
1990	04	10	−281	22
1991	03	25	−298	22
1991	10	29	−254	22
1991	11	09	−354	22
1992	05	10	−288	22
2000	04	07	−288	23
2000	07	16	−301	23
2001	03	31	−387	23
2001	04	11	−271	23
2001	11	06	−292	23
2003	10	30	−383	23
2003	10	30	−353	23
2003	11	20	−422	23
2004	11	08	−374	23
2004	11	10	−263	23

star', respectively (Fig. 1). As for the philological background to these versions, the Ancient Text is a modern scholarly reconstruction of the early text based on the excerpts and citations in extant printed documents of early date, whereas the Current Text is a product of the late evolution of the text with dubious authenticity. Accordingly, we followed the Ancient Text variant, settled on the reported celestial event as the 'five-coloured light', and interpreted this phenomenon as a candidate aurora. The Ancient Text indicated a five-coloured light penetrating Zǐwēi during the night. This description is highly consistent with an auroral interpretation due to its appearance in the circumpolar sky region during the nighttime and the multiple colouration.

The date of this celestial event was determined as 977 ± 1 or 957 ± 1 BCE, following the various chronologies of Shaughnessy and the Xià-Shāng-Zhōu Chronology Project and accommodating uncertainties in the calendar conversion from the historical to the Julian calendar. The observational site was considered to be around the contemporary capital Hàojīng (鎬京: N34°14′, E108°46′) or somewhere on the way of King Zhāo's southward inspection tour. On this basis, we conservatively estimated the equatorial boundary of the auroral visibility to have been down to 39.0° MLAT or 38.9° MLAT. As the five-coloured light reportedly penetrated the circumpolar sky region (Zǐwēi), we conservatively assumed the auroral altitude ≥ 34° and reconstructed the equatorward boundary of the auroral oval (EBAO) as ≤ 45.5° (977 BCE) or ≤ 45.4° (957 BCE). The empirical correlation between the EBAO and storm intensity requires an occurrence of an extreme geomagnetic storm (minimum Dst estimate ≤ − 296 ± 47 nT (977 BCE) or ≤ − 300 ± 48 nT (957 BCE)) for such a large equatorward extension of the auroral oval.

In concluding, we contextualise this candidate auroral record in relation to long-term solar variability. Fig. 2 shows the plausible dates (977 BCE and 957 BCE) in a time series of decadal sunspot numbers reconstructed from cosmogenic isotopes, namely ^{14}C in tree rings and ^{10}Be in ice cores (Usoskin et al. 2014; Wu et al. 2018). The Chinese report predates the Assyrian candidate auroral reports for 679 – 655 BCE (Hayakawa et al. 2019b) by ≈ 3 centuries. The next earliest candidate auroral reports come from the 6th century BCE, *viz.* Ezekiel's vision (Silverman 2006b) with a corrected date in 594 or 593 BCE and reliability caveats (Hayakawa et al. 2019b), and the record of 567 BCE from the Babylonian astronomical diaries (Stephenson et al. 2004; Hayakawa et al., 2016).

Fig. 2 positions the 'five-coloured light' of the *Bamboo Annals* on a local increase of the decadal sunspot number in 980 s – 940 s BCE. Both Usoskin et al. (2014) and Wu et al. (2018) have indicated more significant solar activity for the 950 s BCE than the 970 s BCE. As these decadal reconstructions have not resolved regular sunspot cycles of ≈ 11 years, they have not allowed us to locate this event in a specific solar-cycle phase at that time. This report is temporally separated from the Babylonian and Assyrian reports by a grand solar minimum in *ca.* 810 – 720 BCE (Usoskin, Solanki & Kovaltsov 2007; Usoskin et al. 2014). This grand minimum has occasionally been called the Homeric Grand Minimum (fig. 7 of Landscheidt 1981; see also Silverman & Hayakawa 2021), but could be alternatively — and probably more appropriately — named the Neo-Assyrian Grand Minimum in recognition of the Neo-Assyrian Empire's prominence at the time (Düring, 2020) and the scholarly controversies on Homer's dates and historicity (e.g., Boardman et al., 1986). As this report predates the next known reports of candidate aurorae by ≈ 3 centuries, it should be regarded as the earliest known record of a datable candidate aurora and as the only known hint for a space weather event before the

Neo-Assyrian Grand Minimum (*ca.* 810 – 720 BCE) attested in the historical records so far.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

We have consulted the Chinese printed documents in the National Diet Library (MS Nu-3) and the Institute for Advanced Studies on Asia of the University of Tokyo (MS B1452800). We have derived the reconstructed decadal sunspot number from Usoskin *et al.* (2014) and Wu *et al.* (2018). The Dst index has been derived from the WDC for Geomagnetism at Kyoto.

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