

FULL PAPER

Open Access



Earliest datable records of aurora-like phenomena in the astronomical diaries from Babylonia

Hisashi Hayakawa^{1*}, Yasuyuki Mitsuma², Yusuke Ebihara^{3,4}, Akito Davis Kawamura⁵, Hiroko Miyahara⁶, Harufumi Tamazawa⁵ and Hiroaki Isobe^{4,7}

Abstract

The astronomical diaries from Babylonia (ADB) are excellent sources of information of natural phenomena, including astronomical ones, in pre-Christ era because it contains the record of highly continuous and systematic observations. In this article, we present results of a survey of aurora-like phenomena in ADB, spanning from BCE 652 to BCE 61. We have found nine records of aurora-like phenomena. Philological and scientific examinations suggest that five of them can be considered as likely candidate for aurora observations. They provide unique information about the solar and aurora activities in the first millennium BCE.

Keywords: History of astronomy, Surveys, Solar flares, CMEs, Solar activity, Astronomical diaries from Babylonia

Introduction

The solar activity has been monitored by telescopic observations of sunspots for more than 400 years (Zolotova and Ponyavin 2015; Vaquero and Vázquez 2009; Owens 2013). Reconstructing the earlier solar activity has been of great interest from the viewpoints of the long-term variation of solar magnetism and its effect on the Earth climate (Haigh 2007; Miyahara et al. 2008; Hathaway 2010; Usoskin 2013). One common way to reconstruct the past solar activity is the analysis of cosmogenic radioisotopes such as carbon-14 content in tree rings and beryllium-10 in ice cores (Steinhilber et al. 2009).

Records in historical documents provide another way to investigate the solar activity in the pre-telescopic era (Willis et al. 1996; Vaquero and Vázquez 2009; Usoskin et al. 2007; Usoskin 2013; Hayakawa et al. 2016b, c, submitted). Eddy (1977b, 1980) and Vaquero and Vázquez (2009) even claim that historical documents can offer us data with more precise date than radioactive isotopes.

Chinese official histories (Yau and Stephenson 1988; Yau et al. 1995; Xu et al. 2000; Hayakawa et al. 2015,

2016d, submitted; Kawamura et al. 2016) and Korean official histories (Lee et al. 2004) are especially suitable source documents for the purpose of studying the long-term variation because these sources provide well-formatted records based on continuous observations by professional astronomers (Keimatsu 1976; Hayakawa et al. 2015).

Recently, the past solar activity is also attracting the interest from the viewpoint of extreme space weather (e.g. Tsurutani et al. 2003; Schrijver et al. 2012) particularly after the discoveries of “superflares” in solar-type stars (Maehara et al. 2012; Shibayama et al. 2013; Maehara et al. 2015) as well as the sharp increase in cosmogenic radioisotopes in tree rings around CE775 and CE994 (Miyake et al. 2012, 2013; Mekhaldi et al. 2015), for which one of possible causes are suggested to be large solar flares. The discoveries of “superflares” in solar-type stars posed the question whether such extremely intense solar flares and space weather events can occur in our Sun (e.g. Shibata et al. 2013; Aulanier et al. 2013).

The most intense solar flare throughout the history of telescopic observation is believed to be so-called Carrington event (Carrington 1859; Tsurutani et al. 2003; Cliver and Dietrich 2013). It was associated with worldwide aurora observations by amateur observers, even

*Correspondence: hayakawa@kwasan.kyoto-u.ac.jp

¹ Graduate School of Letters, Kyoto University, Kyoto, Japan

Full list of author information is available at the end of the article

at low geomagnetic latitudes (Loomis 1859, 1860a, c, d, e, 1861a, b, 1865; Kimball 1960; Nakazawa et al. 2004; Green and Boardsen 2006; Hayakawa et al. 2016b). A sharp spike of nitrate in polar ice cores has also been found associated with this event (McCracken et al. 2001), although the usage of nitrate as an index of solar flares is debated (Wolff et al. 2012). Searches for the historical records corresponding to the cosmic ray event in CE775 and CE994 (Miyake et al. 2012, 2013) have been carried out by several groups (Usoskin et al. 2013; Chapman et al. 2015; Stephenson 2015; Hayakawa et al. 2016a, e, submitted).

From the viewpoint of the history of science, it is also interesting to investigate how far back we can trace the solar and space weather events using historical records. Previously, the earliest record was thought to be a Chinese record from BCE 193 (Yau et al. 1995). However, Stephenson and Willis (2002) as well as Stephenson et al. (2004) found a much earlier record from BCE 567 within the astronomical diaries from Babylonia (ADB) to be the oldest observation of aurora in the world and the sole aurora observation in ADB.

In this article, we made further careful examinations of ADB in order to search for the potential records of an aurora and hence to obtain insights into the aurora observations and records in pre-Christ era that were not previously well known due to the shortage of historical documents.

Astronomical diaries from Babylonia

ADB is a series of Akkadian cuneiform texts inscribed on clay tablets. Most of the tablets were rediscovered in excavations at the site of Babylon in the late nineteenth century and now preserved in the British Museum, London. Contemporarily, each text of these tablets was titled “regular observation [*našāru* (EN.NUN) *šā gi-né-e*]”. These records were mostly written and compiled by the families of astronomer–astrologers (*tupšar Enūma Anu Enlil*) sponsored by the assembly of Esangil, the temple of god Marduk in Babylon (N32°33′, E44°26′) (Mitsuma 2012, 2015). The scholars compiled the diaries from generation to generation, at least from the mid-seventh to the mid-first centuries BC. Towards the mid-third century BC, they fixed the format of the diaries, especially of the so-called Longer Diaries or Standard Diaries.

Each tablet of the standard diaries covers half a year, i.e. 6 or 7 months if an intercalary month is included, or a third of a year, i.e. 4 or 5 months including an intercalary month. Horizontal rulings divide each tablet into four, five, six, or seven sections, according to its coverage. Each section covers a month, and its entries are arranged into subjects in the following order: daily report of the sky, price list of commodities, summary of the positions

of the visible planets, level of the Euphrates, and unusual historical event(s).

In this article, we mainly examine the daily sky reports of ADB. They use consistent terminology and have a consistent set of criteria for the choice of what should be recorded. Their observations were carried out continuously as the original title of the diary tablet suggests. The astronomer–astrologers inserted a passage “I did not watch (NU PAP)”, when they could not make their observations (Sachs and Hunger 1988; Mitsuma 2009).

Importantly, we have only fragments of the original ADB series, so our analysis is limited. Although the earliest known tablet in the ADB dates from BCE 652 and the latest up to BCE 61, we have not unearthed or reconstructed all tablets for every month. We have at most 5–10% of the estimated original complete ADB series (Stephenson et al. 2004; see also Sachs 1974). Future reconstruction and deciphering of undated clay tablets could improve this situation at least partially.

Methods

Target keywords and text survey

Within the ADB, we surveyed records that include descriptions of uncategorized luminous phenomena in the sky, excluding the keywords whose meanings are well known, such as “fall of fire, lightning strike (*miqitti išāti*)”, “lightning (*birqu*)”, “thunder (*rigim Adad*)”, “meteor (*kakabu rabū*)”, “comet (*šallammū*)”, “halo (*TÜR/tarbašu*)”, or normal “rainbow (*TIR.AN/manzât*)” shown in the introduction of Sachs and Hunger (1988).

We first surveyed the critical editions of ADB published by Sachs and Hunger (1988, 1989, 1996) and by Hunger and van der Spek (2006). They edited the transliterations of Akkadian texts from all the ADB tablets whose dates became clear by 2006. We then examined the colour photographs recently taken by one of the authors (Y Mitsuma) at the British Museum, and copies made by EF Weidner and TG Pinches.

Date conversion

The Babylonian calendar was a lunisolar calendar. One year consists of 12 lunar months (*arḫu*) or 13 lunar months including an intercalary month. Each day starts at sunset, as is the case in the Bible (Parker and Dubberstein 1956, 26; Sachs and Hunger 1988, 15), each month starts when a new crescent moon is observed, and each year starts at the month around the vernal equinox. The Julian dates of the beginnings of Babylonian months covered by the diaries were calculated by Parker and Dubberstein (1956) and by Sachs and Hunger (1988, 1989, 1996), except for those in BCE651, the oldest diary known to us. Note that these conversion tables only cover up to BCE626. We follow the procedure by Sachs and Hunger to convert Babylonian

dates in this article. Based on the converted dates, we computed normalized lunar ages according to the algorithm of Kawamura et al. (2016) that employs the interactive data language (IDL) programs in the astronomy user IDL library of NASA/Goddard Space Flight Center (Landsman 1993) and our program developed for numerically determining the minimum of lunar luminosity.

Result

In total, we found nine candidates of aurora observations recorded in the ADB. Those we found are shown with their ID numbers, keywords, references, dates in Julian calendar, normalized lunar ages, dates in Babylonian calendar, transliterations of Akkadian texts, and English translations. The notation “-n” such as -651 in every entry is the text number of the diaries published by Sachs and Hunger (1988, 1989, 1996) and Hunger and van der Spek (2006). In the section of Babylonian date, “n/n-1 BC” is used to show the Julian equivalent to a Babylonian year. Babylonian months are shown with roman numerals. For the convention used to indicate a part of a diary, see Sachs and Hunger (1988, 36–38).

#1: *manzât*/(very red) rainbow

Reference: -651 (BM 32312) Col. iv 20': The text was checked using a recently taken photograph of the tablet (Copy: Fig. 1).

Date in Julian Calendar: ?? ?? BCE 651

Normalized lunar age: n/a

Date in Babylonian Calendar: BCE 652/651. XII. 28

Transliteration: 28 ŠĒG *i ina* KIN.SIG TIR *ma-diš* SA₅ *ina* KUR GIB

Translation: The 28th, a little rain. In the afternoon, a very red rainbow stretched in the east.

#2: *akukūtu*/red glow

Reference: -567 (VAT 4956) 'Rev. 10': The text was checked using the copy of the tablet made by EF Weidner, attached as Plate 17 to van der Waerden (1952–1953).

Date in Julian Calendar: 12/13 March BCE 567

Normalized lunar age: 0.003

Date in Babylonian Calendar: BCE 568/567. XI. 29

Transliteration: GE₆ 29 *a-ku₆-ku₆-{ku₆}-tu₄* *ina* ŠÚ KUR 2 DA[NNA....]

Translation: Night of the 29th, red glow flared up in the west; 2 double[-hour....]

#3: *manzât*/rainbow (before sunrise)

Reference: -384 (BM 34634) 'Obv. 4': The text was checked using a recently taken photograph of the tablet (Copy: Fig. 2).

Date in Julian Calendar: 8/9 or 9/10 December BCE 385

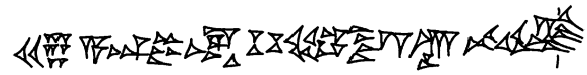


Fig. 1 A copy of #1, -651 Col. iv 20', by Yasuyuki Mitsuma



Fig. 2 A copy of #3, -384 'Obv. 4', by Yasuyuki Mitsuma

Normalized lunar age: 0.260 or 0.294

Date in Babylonian Calendar: BCE 385/384. IX. 8 or 9

Transliteration: [....] *la-am* KUR-*ha* TIR.AN Á SI *u* MAR 'GIB' [....]

Translation: [....] before (sun)rise, a rainbow stretched in the north-west direction [....]

#4: *dipāru*/torch

Reference: -165A (BM 32844) 'Rev. 10'–11' (according to the reconstruction by Sachs and Hunger 1989, 489)

Date in Julian Calendar: 16/17 September BCE 166

Normalized lunar age: 0.142

Date in Babylonian Calendar: BCE 166/165. VI. 4

Transliteration: [4 *ina* še-ri] IZI.GAR TA ULÛ *ana* SI DIB-*ma* UD-DA-*su* [....]

Translation: [The 4th, in the morning,] a “torch” crossed (the sky) from the south to the north, and its bright light [....]

#5: *sūmu*/redness

Reference: -144 (BM 34609 [+]) 34788 + 77617 + 78958) 'Obv. 33'–34': The text was checked with a recently taken photograph of the tablet (Copy: Fig. 3a, b).

Date in Julian Calendar: 21/22 September–19/20 October BCE 145

Normalized lunar age: n/a

Date in Babylonian Calendar: BCE 145/144. VII

Transliteration: ITI BI *su-um i-ša* [ina GI]Š.NIM *u* GIŠ.ŠÚ GAR.GAR-*an*

Translation: That month, a little redness was found repeatedly in the east and in the west.

#6: *sūmu*/redness

Reference: -143A (BM 34045) 'Flake' 21': The text was checked with the copy of TG Pinches, published by Sachs and Hunger (1996, Plate 190).

Date in Julian Calendar: 12/13 July–10/11 August BCE 144

Normalized lunar age: n/a

Date in Babylonian Calendar: BCE 144/143. IV



Fig. 3 Upper part a copy of #5, —144 'Obv. 33' right side, by Yasuyuki Mitsuma. Lower part a copy of #5, —144 'Obv. 34' left side, by Yasuyuki Mitsuma

Transliteration: ITI BI *su-um* [*ina*] GIŠ.NIM u GIŠ.ŠÚ GAR.GAR-*an*

Translation: That month, redness was found repeatedly in the east and in the west.

#7: *dipāru*/torch

Reference: —136B (BM 45745) 'Obv.' 4'–5' (according to the reconstruction by Sachs and Hunger 1996, 182)

Date in Julian Calendar: 10/11 or 11/12 November BCE 137

Normalized lunar age: 0.710 or 0.743

Date in Babylonian Calendar: BCE 137/136. VIII. 20 or 21

Transliteration: ʾ20ʾ [... GE₆ 21ʾ] ʾGIMʾ IZI.GAR SAR-*uh* UD.DA-[*su*] ʾxʾ GAL IGI-LÁ-*át*

Translation: The 20th, [... Night of the 21st (?)] flared up like a torch, [its] bright light was seen.

#8: *manzât*/(red) rainbow

Reference: —122A (BM 45998 + 46049) 'Obv.' 11' (according to the reconstruction by Sachs and Hunger 1996, 290)

Date in Julian Calendar: 28/29 or 29/30 April BCE 123

Normalized lunar age: 0.210 or 0.244

Date in Babylonian Calendar: BCE 123/122. II. 6/7

Transliteration: [x x] ʾúʾ ŠÚ šá sin ^dTIR.AN.NA šá MÚŠ^{meš}-šú SUD TA SI *ana* Á ULÙ [GIB....]

Translation: [...] and (?) setting of the moon, a rainbow whose shine was red [stretched] from the north to the south side [...]

#9: *dipāru*/torch

Reference: —118A (BM 41693) 'Rev. 10': The text was checked using the copy of TG Pinches, published by Sachs and Hunger (1996, Plates 249–251)

Date in Julian Calendar: 24/25 October BCE 119

Normalized lunar age: 0.754

Date in Babylonian Calendar: BCE 119/118. VII. 22

Transliteration: [... SAG] GE₆ IZI.GAR TA KUR *ana* MAR SUR-*ma* SUR-šú *ma-gal* BABBAR

Translation: [...] beginning] of the night, a torch flashed from east to west, and its flash was very white.

Discussion

In our survey of the ADB, we found nine records that can be considered as the candidates for aurora observations. They can be categorized using the following keywords: unusual "rainbow (TIR.AN/*manzât*)" (#1, 3, 8), "red glow (*akukūtu*)" (#2), "redness (*sūmu*)" (#5, 6), and "torch (IZI.GAR/*dipāru*)" (#4, 7, 9).

Red glow: *akukūtu*

The record #2 is the well-known record from Stephenson et al. (2004), where the term was introduced and examined philologically and scientifically. The term *akukūtu* means "flame, blaze" or "red glow in the sky (as a rare meteorological phenomenon)" (CAD: I-1, p. 285). It is the second meaning that appears in this sentence. CAD (*The Assyrian Dictionary of the Oriental Institute of the University of Chicago*) relates this term to aurora as well.

Stephenson et al. (2004) made a positive interpretation of #2 because its last signs—2 DANNA—"2 double hours" indicate the duration of the phenomenon, and there is no other light source that can supply red light for as long as 4 h. Their conclusion can be reinforced with the flat topography in Babylonia. Babylon is located in the alluvial plain caused by the rivers of Euphrates and Tigris, in an area with no mountains until the Zagros Mountains about 180 km away in the north-east. Its weather is very dry, allowing few trees to grow. This means there is nowhere that a mountain fire or long-lasting light can be caused on the ground.

Unusual rainbow: TIR.AN (*manzât*)

^(d)TIR.AN(.NA) (*manzât*) of #3 and #8 usually means as "rainbow" or "a name of star" or sometimes as "halo" with a subsequent description such as "surrounding the sun/moon" (CAD, X-1, pp. 230–232). #1 shows TIR. It seems to be an abbreviated form of TIR.AN and is followed by the words *ma-diš* SA₅ "very red", as is suggested by the comment of Sachs and Hunger (1988, p. 46) to #1. *manzât* was used with the verb GIB (*parāku*) "stretch" in #1 and #3, and the same verb may be restored in #8. These "rainbows" appear "stretched" in the sky with a red colour (#1, #8) or at night (#3, #8). Since these appearances do not match the nature of normal rainbows, *manzât* in #1, #3, and #8 seem to have been something different.

The unusual "rainbow" or TIR.AN in #3 was observed "before sunrise". The lunar age of this event is about 0.3 with the moon at about the waxing quarter, and the moon had already set at this time "before sunrise". Therefore, moonbow or any other moon-related atmospheric

optical phenomenon cannot explain this event. Considering that this event was seen in the northern direction, which is usual for low-latitude auroras, it is reasonable to leave this record as the candidate for an aurora observation.

The term ^dTIR.AN.NA (*manzât*) in #8 is recorded after the “setting of the moon”. The exact observational date is broken in the original tablet. However, this record is located between the record for BCE 123/122. II. 5 and that for BCE 123/122. II. 8 and thus can be located on II. 6/7, namely on 28/29 or 29/30 April BCE 123. Its moon phase is 0.227 or 0.261, and thus, the moon was approximately in its waxing quarter. This means “after moonset” was equivalent to just after midnight. This red “rainbow” may be regarded as an auroral arc elongated “from north to south” across the sky.

The unusual “rainbow” or TIR in #1 was also red in colour. Unfortunately, the Julian date of this record (BCE 652/651. XII. 28) was not calculated by Sachs and Hunger (1988) nor by Parker and Dubberstein (1956). Despite its abnormality, this record is very unlikely to represent aurora due to the observation time being “in the afternoon (KIN.SIG)”. Red rainbows can be observed especially at the time of twilight when red-coloured light from the sun gets refracted by waterdrops. The “rain” immediately before this phenomenon might have supplied the waterdrops to cause rainbows in the quite dry weather in Babylonia.

Nevertheless, we should note two historical reports for luminescence phenomena observed in the day time in a huge magnetic storm, namely in the Carrington event. Loomis (1860b) cited a letter from Lieut. N. Home to describe aurora observation at Halifax on 28 August 1859. At 17:00, “a long narrow belt of cloud from E. to W. having a peculiar orange-white appearance” was seen, and at 20:00 “this cloud suddenly became luminous at its eastern extremity”. This cloud is unlikely to have been aurora in the day time, but we cannot rule out the possibility that it was aurora.

Meanwhile, “unusual rainbow” can sometimes be related to bow-shaped auroras worldwide. A Norwegian drawing for aurora on 26 November 1710 was drawn like a rainbow in Ramus (1745), and Chinese historians reported some auroras as “white/unusual rainbow” in their official histories as highlighted by Hayakawa et al. (2016a).

Redness: *sūmu*

The term *sūmu* used in #5 and #6 means “redness, red glow” or “red spot”. While the term in the latter meaning is used for red spots on the body, the term in the former meaning is used in astronomical contexts (CAD: XV, pp. 381–383). The *sūmu* of #5 and #6 was probably celestial

events, although they appear not in reports of celestial events but in reports of historical events. Those observations of “redness” might have been considered as omens for historical events and recorded with them. Another celestial event, for example, lightning strike (*miqitti išāti*), is often inserted into the historical parts of the diaries and seems to have an ominous significance (Pirngruber 2013).

These terms of “redness” are used almost in the same expression with the signs GAR.GAR-*an*, which represents the Akkadian verb *ittaškan*, Ntn, i.e. passive habitative iterative (Caplice and Snell 2002: pp. 51–52), preterite of *šakānu* “to place”. This indicates that the “redness” of #5 and #6 appeared repeatedly.

These philological analyses show us that “redness” appeared repeatedly in the same month in both cases. This phrase may describe low-latitude auroras whose movement is quite slow and which thus seem to remain in the same place for a long time. During the Halloween storm (29–31 October 2003), aurora observations were made for 3 successive nights (Shiokawa et al., 2005). Alternatively, this phrase is likely to describe a stable red auroral (SAR) arc that can be seen as red, faint lights. Data from optical imaging on board Dynamics Explorer 1 show a SAR arc lasting for 28 h (Craven et al., 1982). In fact, auroras can appear repeatedly for several days when complex active regions on the sun continue to launch multiple coronal mass ejections. At the Carrington event, the strong magnetic storms brought a cluster of auroras to the earth from 1859/08/28 to 09/04 (Loomis 1859, 1860a, c, d, e, 1861a, b, 1865; Kimball 1960; Green and Boardson 2006; Hayakawa et al. 2016b). In September 1770, a series of aurora observation were made in East Asia for at least three days straight (Willis et al. 1996; Kawamura et al. 2016). These records (both #5 and #6) suggest the possibility of strong solar activity in BCE 145–144. In summary, although it is slightly mysterious that they appeared in the east and west, these records are not contradictory with aurora records.

Torches: IZI.GAR (*dipāru*)

This term “IZI.GAR (*dipāru*)” from records #4, #7, and #9 means “torch” (CAD: III, pp. 156–157). The phrase “*ḫakukūtu*, which is like *dipāru*”, appears once in a divination text (Vroelleud 1911–1912, no. 107:3).

Record #4 involves a verb “DIB (*etēqu*)”. This is a motion verb meaning “to pass/go along” (CAD: IV, p. 384; Sachs and Hunger 1988, p. 30). This means that the “torch” in #4 moved from south to north and is probably a meteor or a fireball. If we interpret this record as aurora, we could relate this with expansion and contraction of the aurora oval.

Phenomenon of record #9 has an extension from east to west. The problem is to identify if this is with motion. Its verb “SUR (*ṣarāḥu*)” means “to light up”, “to flare up”, or “to display a sudden luminosity” (CAD: XVI, p. 100). This verb itself does not provide an answer to our question whether this recorded phenomenon appeared without motion. There is a possibility that this is aurora. Bright aurora looks white or greenish white because it consists of emissions from O (green colour) and from N₂ and N₂⁺ (red and blue colours). After auroral breakups, bright aurora expands towards the north and west. The leading edge of the bright aurora is called a westward travelling surge. The westward travelling surge moves westward, but it is unclear whether such an elongated structure is expressed as a torch. Thus, this reminds us of a fireball.

As for record #7, its subject is lost. This makes any detailed discussion difficult. However, something like “a torch” appeared with “UD.DA (*ṣētu*, bright light)”. The word *ṣētu* frequently refers the light of the sun or the moon (CAD: XVI, pp. 150–153). Therefore, strong brightness, at least, seems to be associated with this recorded phenomenon. According to the date written in the clay tablet, its date is 10/11 or 11/12 November BCE 137. In case if it is observed at daytime, we can hardly regard this event as aurora. In case if it is observed at night on 11/12, we have still a little possibility to regard this event as aurora. We have examples for low-latitude aurora, which becomes partially brighter (Shiokawa et al. 2005). Thus, we cannot exclude the possibility of aurora for this record.

Likelihood of every record

Based on the analysis above, we can rate these aurora-like records as follows (Table 1). #2 has no reason not to be related to aurora as Stephenson et al. (2004) stated. The same can be stated for the “redness” in #5 and #6. They appeared repeatedly and remind us of clustering aurora caused by huge geomagnetic storms like those

at the Carrington event. The unusual “rainbows” in #3 and #8 are not unlike aurora, since these rainbows are observed at night. Despite the same terminology, #1 is unlikely to be aurora due to its daytime observation. #4 and #9 seem like fireballs or meteors from the descriptions, and we do not have any positive intention to relate them with aurora. #7 could be aurora as the term *dipāru* can be used for description of *ḥakukūtu*, a variant of *akukūtu*, which can mean aurora, though its subject is lost and we cannot make a clear conclusion on this.

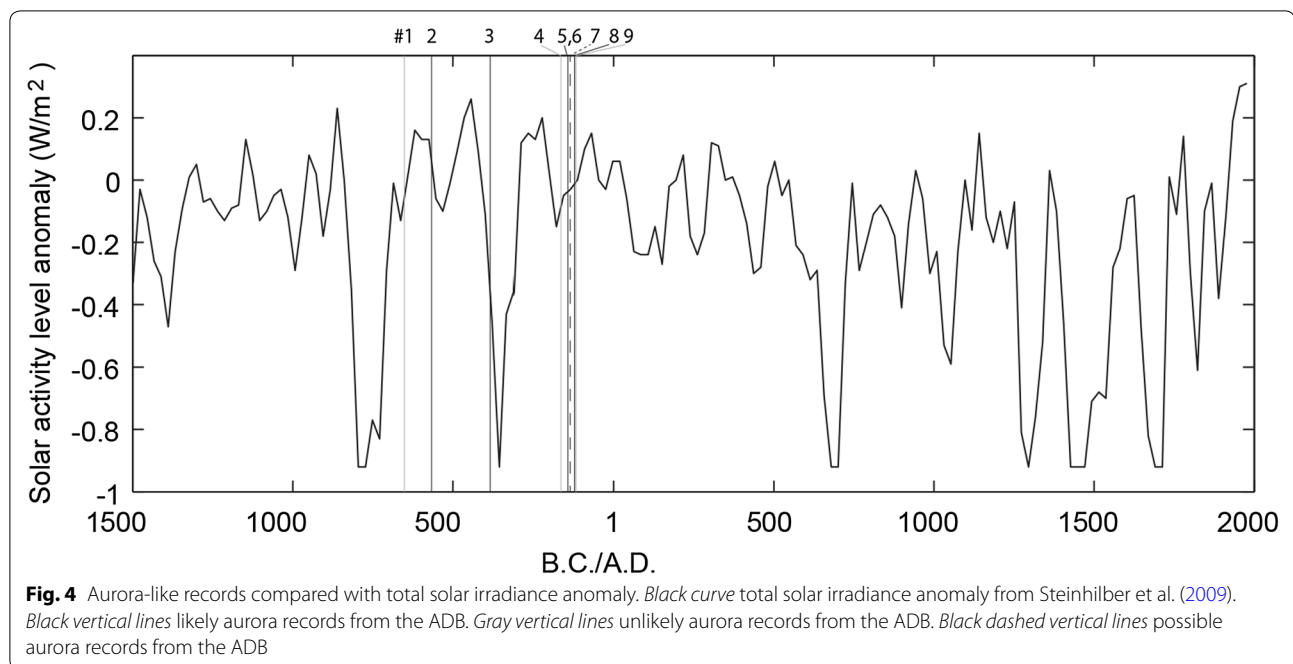
Korte and Stolze (2014) estimated the location of the aurora zone for past 10,000 years. During the period spanning from BCE 652 to BCE 61, Babylon was situated near the centre of the two boundaries where aurora was visible on the horizon at the geomagnetic activity levels Kp = 4 and Kp = 9. According to the statistical study by Remick and Love (2006), the mean wait times between successive events are 7.12, 16.55, 42.22, and 121.40 days for Kp ≥ 5, 6, 7, and 8, respectively. Thus, it is quite likely that aurora was frequently visible at Babylon somewhere between the horizon and zenith.

Comparison with long-term solar activity

In order to map the aurora-like records shown above with long-term solar activity, we compared the dates of these records with proxy-based solar activity levels. Figure 4 shows a comparison of the aurora-like records with the solar activity level anomaly reconstructed using multiple proxies of radioactive isotopes by Steinhilber et al. (2009) at a resolution of 20–30 years. However, it should also be noted that this comparison between characteristics of the solar activity at different timescales is hard and complex, as on one hand auroras occur at daily scale, and on the other hand, the reconstruction of solar activity by Steinhilber et al. (2009) has a decadal time resolution (see Vaquero et al. 2002 for the similar problems in case of naked-eye observations of sunspots).

Table 1 Summary table for records of aurora-like phenomena in ADB

ID	Year (BCE)	Month	Date	Keyword	Direction	Likelihood
#1	651	??	??	<i>manzât</i>	E	Unlikely
#2	567	3	12/13	<i>akukūtu</i>	W	Likely
#3	385	12	8/9 or 9/10	<i>manzât</i>	NW	Likely
#4	166	9	16/17	<i>dipāru</i>	S–N	Unlikely
#5	145	9/10		<i>sūmu</i>	E and W	Likely
#6	144	7/8		<i>sūmu</i>	E and W	Likely
#7	137	11	10/11 or 11/12	<i>dipāru</i>		Possible
#8	123	4	28/29 or 29/30	<i>manzât</i>	N–S	Likely
#9	119	10	24/25	<i>dipāru</i>	E–W	Unlikely



This figure shows us that most of the aurora-like records, except for #3 in BC 385 in solar minimum (Eddy 1977a, b; Usoskin et al. 2007; Nagaya et al. 2012), are located in phases of high solar activity. The cases #5–#7 are clustered in BCE 140–130 s, and #8–#9 are around BCE 120. These peaks are comparable with contemporary aurora records from other regions. For the former peak, red vapour was recorded in BCE 139 in Chinese official history *Hànshū* (Yau et al. 1995), and reports of sky fire in BCE 147 and night sun in BCE 134 in Western classics (Stothers 1979). For the latter peak, we have reports of milk rain in BCE 124 and BCE 118 in Western classics (Stothers 1979). Although we do not have exact simultaneous observation of aurora, these clustering records support the peaks at both BCE 140 s–130 s and around BCE 120 shown in the ADB.

Conclusion

We surveyed aurora-like records in ADB spanning from BCE 652 to BCE 61. We found 9 records of aurora-like phenomena including one mentioned in Stephenson et al. (2004) and examined them to evaluate 5 likely, 3 unlikely, and 1 possible aurora event. The main characteristics of these events are provided in this article. Our result is quite consistent with the long-term solar activity level, although comparison between characteristics of the solar activity at different timescales has difficulties as stated above. This article rewrites the history of aurora observation in this early period with dates to provide clear insights for the era before Christ. This article also

examines proxies at a high resolution in this early period in order to consider long-term solar activity and rare extreme space weather events. A lot of unpublished clay tablets of the ADB are preserved in the British Museum. Although most of them are fragmentary, study of those tablets will provide us further astronomical information from the mid-seventh to the mid-first centuries BCE, possibly including further records of aurora-like phenomena.

Abbreviations

BM: tablets in the collections of the British Museum; VAT: tablets in the collections of the Staatliche Museen, Berlin.

Authors' contributions

This research was performed with the cooperation of authors as follows: HH and YM made historical and philological contributions. ADK, YE, and HT made contributions on scientific interpretations and analyses. HM compared and discussed records with long-term solar activity. HI supervised this study. All authors read and approved the final manuscript.

Author details

¹ Graduate School of Letters, Kyoto University, Kyoto, Japan. ² Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, Japan. ³ Research Institute for Sustainable Humanosphere, Kyoto University, Kyoto, Japan. ⁴ Unit of Synergetic Studies for Space, Kyoto University, Kyoto, Japan. ⁵ Kwasan Observatory, Kyoto University, Kyoto, Japan. ⁶ Musashino Art University, Tokyo, Japan. ⁷ Graduate School of Advanced Integrated Studies for Human Survivability, Kyoto University, Kyoto, Japan.

Acknowledgements

We thank the Trustees of the British Museum for allowing the study and photography of the tablets BM 32312, BM 34609 (+) 34788 + 77617 + 78958, and BM 34634. We acknowledge support from the Center for the Promotion of Integrated Sciences (CPIS) of SOKENDAI as well as Kyoto University's Supporting Program for Interaction-based Initiative Team Studies "Integrated

study on human in space" (Pl: H. Isobe), the Interdisciplinary Research Idea contest 2014 by the Center of Promotion Interdisciplinary Education and Research, the "UCHUGAKU" project of the Unit of Synergetic Studies for Space, and the Exploratory Research Projects of the Research Institute of Sustainable Humanosphere, Kyoto University. This work was also supported by Grant-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology of Japan, Grant Numbers JP 15H05816 (Pl: S. Yoden), JP 26870111 (Pl: Y. Mitsuma), and JP 15H05815 (Pl: Y. Miyoshi).

Competing interests

The authors declare that they have no competing interests.

Received: 8 October 2016 Accepted: 17 November 2016

Published online: 29 November 2016

References

- Aulanier G, Démoulin P, Schrijver CJ, Janvier M,ariat E, Schmieder B (2013) The standard flare model in three dimensions. II. Upper limit on solar flare energy. *A&A* 549:7. doi:10.1051/0004-6361/201220406
- CAD: Oppenheim AL, Reiner E et al (eds) (1956–2010) The Assyrian dictionary of the Oriental Institute of the University of Chicago, vol 21, Chicago
- Caplice R, Snell D (2002) Introduction to Akkadian. Gregorian Biblical Book-Shop, Rome
- Carrington RC (1859) Description of a singular appearance seen in the Sun on September 1, 1859. *MNRAS*, vol 20. doi:10.1093/mnras/20.1.13
- Chapman J, Neuhauser DI, Neuhauser R, Csikszentmihalyi M (2015) A review of East Asian reports of aurorae and comets circa AD 775. *Astron Nachr* 88:789–804. doi:10.1002/asna.201512193
- Cliver EW, Dietrich WF (2013) The 1859 space weather event revisited: limits of extreme activity. *J Space Weather Space Clim* 3:A31. doi:10.1051/swsc/2013053
- Craven JD, Frank LA, Ackerson KL (1982) Global observations of a SAR arc. *GRL* 9:961–964. doi:10.1029/GL009i009p00961
- Eddy JA (1977a) The case of the missing sunspots. *Sci Am* 236:80–88. doi:10.1038/scientificamerican0577-80
- Eddy JA (1977b) Climate and the changing Sun. *Clim Change* 1:173–190
- Eddy JA (1980) The historical record of solar activity. In: The ancient Sun: Fossil record in the earth, moon and meteorites. In: Proceedings of the conference, Boulder, CO, 16–19 Oct 1979. (A81-48801 24-91). Pergamon Press, New York, pp 119–134
- Green J, Boardsen S (2006) Duration and extent of the great auroral storm of 1859. *Adv Space Res* 38(2):130–135. doi:10.1016/j.asr.2005.08.054
- Haigh JD (2007) The Sun and the Earth's climate. *Living Rev Solar Phys* 4:2. doi:10.12942/lrsp-2007-2
- Hathaway DH (2010) The solar cycle. *Living Rev Solar Phys* 7:1. doi:10.12942/lrsp-2010-1
- Hayakawa H, Tamazawa H, Kawamura AD, Isobe H (2015) Records of sunspot and aurora during CE 960–1279 in the Chinese chronicle of the Song dynasty. *EPS* 67:82. doi:10.1186/s40623-015-0250-y
- Hayakawa H, Isobe H, Kawamura AD, Tamazawa H, Miyahara H, Kataoka R (2016a) Unusual rainbow and white rainbow: a new auroral candidate in oriental historical sources. *PASJ* 68(3):33. doi:10.1093/pasj/psw032
- Hayakawa H, Iwahashi K, Tamazawa H, Isobe H, Kataoka R, Ebihara Y, Miyahara H, Kawamura AD, Shibata K (2016b) East Asian observations of low latitude aurora during the Carrington magnetic storm. *PASJ*. doi:10.1093/pasj/psw097 (first published online)
- Hayakawa H, Mitsuma Y, Fujiwara Y, Kawamura AD, Kataoka R, Ebihara Y, Kosaka S, Iwahashi K, Tamazawa H, Isobe H (2016c) The earliest drawings of datable auroras and a two-tail comet from the Syriac Chronicle of Zūqnīn. *PASJ*. arxiv:1610.08690 (accepted)
- Hayakawa H, Tamazawa H, Ebihara Y, Miyahara H, Kawamura AD, Aoyama T, Isobe H (2016d) Records of sunspots and aurora candidates in the Chinese Official Histories of the *Yudn* and *Ming* dynasties. *PASJ* (submitted)
- Hayakawa H, Tamazawa H, Uchuyama Y, Ebihara Y, Miyahara H, Kosaka S, Iwahashi K, Isobe H (2016e) Historical aurora evidences for great magnetic storms in 990s. *Sol Phys* (submitted)
- Hunger H, van der Spek RJ (2006) An astronomical diary concerning Artaxerxes II (Year 42 = 363-2 BC): military operations in Babylonia. *Arta*, no. 002, 1-16
- Kawamura AD, Hayakawa H, Tamazawa H, Miyahara H, Isobe H (2016) Aurora candidates from the chronicle of *Qing* dynasty in several degrees of relevance. *PASJ* 68(5):79. doi:10.1093/pasj/psw074
- Keimatsu (1976) Chronology of aurorae and sunspots observed in China, Korea and Japan. Annual of Science, College of Liberal Arts, Kanazawa University, Part 7, vol 13, pp 1-32
- Kimball DS (1960) A study of the aurora of 1859. Scientific Report No. 6, University of Alaska, No. 6
- Korte M, Stolze S (2014) Variations in mid-latitude auroral activity during the Holocene. *Archaeometry* 58:159–176. doi:10.1111/arc.12152
- Landsman WB (1993) The IDL astronomy user's library. Astronomical data analysis software and systems II, A.S.P. conference series, vol 52
- Lee E, Ahn Y, Yang H, Chen K (2004) The sunspot and auroral activity cycle derived from Korean historical records of the 11th–18th century. *Sol Phys* 224:373–386. doi:10.1007/s11207-005-5199-8
- Loomis E (1859) The great auroral exhibition of August 28th to September 4th, 1859 (1st article). *Am J Sci, Second Series*, 29, 84:385–408
- Loomis E (1860a) The great auroral exhibition of August 28th to September 4th, 1859 (2d article). *Am J Sci, Second Series*, 29, 85:92–97
- Loomis E (1860b) The Great Auroral Exhibition of August 28th to September 4th, 1859 (3d article). *Am J Sci, Second Series*, 29, 86:249–265
- Loomis E (1860c) The great auroral exhibition of August 28th to September 4th, 1859 (4th article). *Am J Sci, Second Series*, 29, 87:386–397
- Loomis E (1860d) The great auroral exhibition of August 28th to September 4th, 1859 (5th article). *Am J Sci, Second Series*, 30, 88:79–94
- Loomis E (1860e) The great auroral exhibition of August 28th to September 4th, 1859 (6th article). *Am J Sci, Second Series*, 30, 90:339–361
- Loomis E (1861a) The great auroral exhibition of August 28th to September 4th, 1859 (7th article). *Am J Sci, Second Series*, 32, 94:71–84
- Loomis E (1861b) The great auroral exhibition of August 28th to September 4th, 1859 (8th article). *Am J Sci, Second Series*, 32, 96:318–331
- Loomis E (1865) The aurora borealis, or polar light; its phenomena and laws. Annual report of the Smithsonian institute, pp 208–248
- Maehara H, Shibayama T, Notsu S, Notsu Y, Nagao T, Kusaba S, Honda S, Nogami D, Shibata K (2012) Superflares on solar-type stars. *Nature* 485:478–481. doi:10.1038/nature11063
- Maehara H, Shibayama T, Notsu Y, Notsu S, Honda S, Nogami D, Shibata K (2015) Statistical properties of superflares on solar-type stars based on 1-min cadence data. *EPS* 67:59
- McCracken KG, Dreschhoff GAM, Zeller EJ, Smart DF, Shea MA (2001) Solar cosmic ray events for the period 1561–1994: 1. Identification in polar ice. *JGR* 106(A10):21,585–21,598. doi:10.1029/2000JA000237
- Mekhaldi F, Muscheler R, Adolphi F, Beer AAJ, McConnell JR, Possnert G, Sigl M, Svensson A, Synal H-A, Welten KC, Woodruff TE (2015) Multiradionuclide evidence for the solar origin of the cosmic-ray events of AD 774/5 and 993/4. *Nat Commun* 6:8611. doi:10.1038/ncomms9611
- Mitsuma Y (2009) Royal officials and the city of Babylon in the Seleucid and Arsacid Periods: a study of "Diaries". Tokyo. Doctor thesis
- Mitsuma Y (2012) Astrology and astronomy in the Babylonian astronomical diaries. In: Tsuruoka Y, Fukasawa H (eds) Spirituality and the history of religion, vol 2. Lithon, Tokyo, pp 35–51 (in Japanese)
- Mitsuma Y (2015) From preliminary diaries to short diaries: the first and the second steps in the compilation process of the late Babylonian astronomical diaries. *SCIAMVS* 16:53–73
- Miyahara H, Yokoyama Y, Masuda K (2008) Possible link between multi-decadal climate cycles and periodic reversals of solar magnetic field polarity. *Earth Planet Sci Lett* 272:290–295. doi:10.1016/j.epsl.2008.04.050
- Miyake F, Nagaya K, Masuda K, Nakamura T (2012) A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan. *Nature*. doi:10.1038/nature11123
- Miyake F, Masuda K, Nakamura T (2013) Another rapid event in the carbon-14 content of tree rings. *Nat Commun* 4:1748. doi:10.1038/ncomms2783
- Nagaya K, Kitazawa K, Miyake F, Masuda K, Muraki Y, Nakamura T, Miyahara H, Matsuzaki H (2012) Variation of the Schwabe cycle length during the grand solar minimum in the 4th century BC deduced from radiocarbon content in tree rings. *Solar Phys* 280:223–236. doi:10.1007/s11207-012-0045-2

- Nakazawa Y, Okada T, Shiokawa K (2004) Understanding the “SEKKI” phenomena in Japanese historical literatures based on the modern science of low-latitude aurora. *EPS* 56:e41–e44. doi:[10.1186/BF03353323](https://doi.org/10.1186/BF03353323)
- Owens B (2013) Slow science. *Nature* 495(7441):300–303. doi:[10.1038/495300a](https://doi.org/10.1038/495300a)
- Parker RA, Dubberstein WH (1956) *Babylonian chronology: 626 B.C.–A.D. 75*. Providence. The University of Chicago Press, USA
- Pirngruber R (2013) The historical sections of the astronomical diaries in context: developments in a late Babylonian scientific text corpus. *Iraq* 75:197–210
- Remick KJ, Love JJ (2006) Statistical modeling of storm-level Kp occurrences. *GRL* 33:L16102. doi:[10.1029/2006GL026687](https://doi.org/10.1029/2006GL026687)
- Sachs AJ (1974) Babylonian observational astronomy. *Philos Trans R Soc Lond A* 276:43–50
- Sachs AJ, Hunger H (1988) *Astronomical diaries and related texts from Babylonia*, Vienna, I. Verlag der Österreichischen Akademie der Wissenschaften
- Sachs AJ, Hunger H (1989) *Astronomical diaries and related texts from Babylonia*, Vienna, II. Verlag der Österreichischen Akademie der Wissenschaften
- Sachs AJ, Hunger H (1996) *Astronomical diaries and related texts from Babylonia*, Vienna, III. Verlag der Österreichischen Akademie der Wissenschaften
- Schrijver CJ, Beer J, Baltensperger U et al (2012) Estimating the frequency of extremely energetic solar events, based on solar, stellar, lunar, and terrestrial records. *JGR* 117:A08103. doi:[10.1029/2012JA017706](https://doi.org/10.1029/2012JA017706)
- Shibata K, Isobe H, Hillier A, Choudhuri AR, Maehara H, Ishii TT, Shibayama T, Notsu S, Notsu Y, Nagao T, Honda S, Nogami D (2013) Can superflares occur on our Sun? *PASJ* 65(3):49. doi:[10.1093/pasj/65.3.49](https://doi.org/10.1093/pasj/65.3.49)
- Shibayama T, Maehara H, Notsu S, Notsu Y, Nagao T, Honda S, Ishii TT, Nogami D, Shibata K (2013) Superflares on solar-type stars observed with Kepler. I. Statistical properties of superflares. *Astrophys J* 209(Suppl):5. doi:[10.1088/0067-0049/209/1/5](https://doi.org/10.1088/0067-0049/209/1/5)
- Shiokawa K, Ogawa T, Kamide Y (2005) Low-latitude auroras observed in Japan: 1999–2004. *J Geophys Res* 110:A05202. doi:[10.1029/2004JA010706](https://doi.org/10.1029/2004JA010706)
- Steinhilber F, Beer J, Fröhlich C (2009) Total solar irradiance during the Holocene. *GRL*. doi:[10.1029/2009GL040142](https://doi.org/10.1029/2009GL040142)
- Stephenson FR (2015) Astronomical evidence relating to the observed ^{14}C increases in A.D. 774–5 and 993–4 as determined from tree rings. *Adv Space Res* 55(6):1537–1545. doi:[10.1016/j.asr.2014.12.014](https://doi.org/10.1016/j.asr.2014.12.014)
- Stephenson FR, Willis DM (2002) The earliest datable observation of the aurora borealis. In: Steele JM, Imhausen A (eds) *Under one sky: astronomy and mathematics in the ancient Near East*. Ugarit-Verlag, Münster
- Stephenson FR, Willis DM, Hallinan TJ (2004) The earliest datable observation of the aurora borealis. *A&G* 45(6):615–617. doi:[10.1046/j.1468-4004.2003.45615.x](https://doi.org/10.1046/j.1468-4004.2003.45615.x)
- Stothers R (1979) Ancient aurorae. *Isis* 70(1):85–95
- Tsurutani BT, Gonzalez WD, Lakhina GS, Alex S (2003) The extreme magnetic storm of 1–2 September 1859. *JGR*, 108, SSH 1–1, CiteID 1268. doi:[10.1029/2002JA009504](https://doi.org/10.1029/2002JA009504)
- Usoskin IG (2013) A history of solar activity over millennia. *Living Rev Solar Phys* 10:1. doi:[10.12942/lrsp-2013-1](https://doi.org/10.12942/lrsp-2013-1)
- Usoskin IG, Solanki SK, Kovaltsov GA (2007) Grand minima and maxima of solar activity: new observational constraints. *A&A* 471:301–309. doi:[10.1051/0004-6361:20077704](https://doi.org/10.1051/0004-6361:20077704)
- Usoskin IG, Kromer B, Ludlow F, Beer J, Friedrich M, Kovaltsov GA, Solanki SK, Wacker L (2013) The AD775 cosmic event revisited: the Sun is to blame. *A&A* 552:L3. doi:[10.1051/0004-6361/201321080](https://doi.org/10.1051/0004-6361/201321080)
- Van der Waerden BL (1952–1953) History of the Zodiac. *Archiv für Orientforschung* 16:216–230
- Vaquero JM, Vázquez M (eds) (2009) *The Sun recorded through history*. Springer, Berlin
- Vaquero JM, Gallego MC, García JA (2002) A 250-year cycle in naked-eye observations of sunspots. *GRL* 29(20):58–1–58–4. doi:[10.1029/2002GL014782](https://doi.org/10.1029/2002GL014782)
- Violellaud Ch (1911–1912) *L'astrologie chaldéenne*. 2nd Supplement, Paris
- Willis DM, Stephenson FR, Singh JR (1996) Auroral observations on AD 1770 September 16: the earliest known conjugate sightings. *QJRAS* 25(2):417–436
- Wolff EW, Bigler M, Curran MAJ, Dibb JE, Frey MM, Legrand M, McConnell JR (2012) The Carrington event not observed in most ice core nitrate records. *GRL* 39:L08503. doi:[10.1029/2012GL051603](https://doi.org/10.1029/2012GL051603)
- Xu Z, Pankaniar DW, Jiang Y (2000) East asian archaeoastronomy: historical records of astronomical observations of China. Japan and Korea, Amsterdam
- Yau KKC, Stephenson FR (1988) A revised catalogue of Far Eastern observations of sunspots (165 BC to AD 1918). *QJRAS* 29:175–197
- Yau KKC, Stephenson FR, Willis DM (1995) A catalogue of auroral observations from China, Korea and Japan (193 BC–AD 1770). Rutherford Appleton Laboratory, Chilton (UK), Dec 1995, IV + 82 p., ISSN 1358-6254
- Zolotova NV, Ponyavin DI (2015) The Maunder minimum was not as grand as it seemed to be. *APJ* 800:42. doi:[10.1088/0004-637X/800/1/42](https://doi.org/10.1088/0004-637X/800/1/42)

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Immediate publication on acceptance
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► springeropen.com