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Historical aurora borealis catalog for Anatolia and Constantinople (hABcAC) during the Eastern Roman Empire period: implications for past solar activity

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Abstract. Herein, Anatolian aurorae are reviewed based on the existing catalogs to establish a relationship between the aurora observations and past solar activity during the Medieval period. For this purpose, historical aurora catalogs for Constantinople and Anatolia are compiled based on the existing catalogs and compared with those in the Middle East region. The available catalogs in the literature are mostly related to the records observed in Europe, Japan, China, Russia, and the Middle East. There is no study dealing only with the historical aurora observations recorded in Anatolia and Constantinople. The data of the catalog show that there is a considerable relationship between the aurora activity and past strong solar activity. High auroral activity around the extreme solar particle storm in 774/775 and the Medieval grand maximum in the 1100s in Anatolia and the Middle East is quite consistent with the past solar variability reported in other scientific literature.

1 Introduction

A number of researchers presented the low- and middle-latitude aurora catalogs (Table 1) from Europe (Mairan, 1733; Frobesius, 1739; Fritz, 1873; Schove, 1948; Link, 1962; Dall'Olmo, 1979; Stothers, 1979; Krivsky and Pejml, 1988; Vaquero et al., 2010; Scafetta and Willson, 2013), Arabic countries (Basurah, 2006), Japan (Matsushita, 1956; Nakazawa et al., 2004; Kataoka et al., 2017), and China (Schove and Ho, 1959; Keimatsu, 1976; Hayakawa et al., 2015; Kataoka and Iwahashi, 2017). Aurorae are the most majestic luminous phenomenon observed in the sky. The aurora observations were described as "a sign", "a fiery shining sign", "a very fabulous sign", "red sky", "a fiery red sky", "sky fire", "a great fire", "a fiery cloud", "a frightful and strange omen", "a fire-like omen", "a bloody spear light", "blaze of light", and "a sunlight light". The form of aurorae was defined as a "luminous column".

The historical aurora catalogs have been used to recognize past solar activities (Siscoe, 1980; Silverman, 1992; Schröder, 1992, 1994; Basurah, 2006; Vazquez et al., 2006; Hayakawa et al., 2015), Earth's climate change (Pang and Yau, 2002; Schröder, 2004; Gallet et al., 2005; Bard and Frank, 2006; Scafetta, 2012), and perception of human civilizations (Schröder, 2004; Gallet et al., 2006; Silverman, 2006). Korte and Stolze (2016) showed that the intensity and tilt of the geomagnetic field and high solar activity are closely related to the aurora occurrence. The state of the geomagnetic field and the form of the magnetosphere completely control the location of the auroral zone (Korte and Stulze, 2016). The visibility of the aurorae at low latitudes is very scarce and closely connected with the strong geomagnetic storms related to the high-speed solar wind or interplanetary transients (Eather, 1980; Basurah, 2006; Vazquez et al., 2006).

Mairan (1733) showed that the first scientific monography covers a list of 229 historical aurorae during the period of 502–1731. In 1852, Wolf noticed that the aurorae match with periods of high sunspot number, according to the historical aurora catalog including more than 6300 records (Wolf, 1857). Fritz (1873), who listed 77 European aurora records during 1707–1708, published the historical auroral catalog and separated auroral sightings into five categories based on the latitude and longitude (Schröder, 1994). Link (1962) published a useful aurora catalog seen in European countries based on eight previous catalogs com-

Table 1. Historical aurora catalogs compiled by different authors.

Existing catalogs	Number of Observations	Region	Period
Link (1962)	385	Europe	626 BC–1600 AD
Link (1964)	209	Europe	1600–1700 AD
Stothers (1979)	67	Greece and Italy	480 BC–333 AD
Newton (1972)	65	Europe	450–1263 AD
Dall'Olmo (1979)	61	Europe	450–1461 AD
Keimatsu (1976)	260	China, Korea, and Japan	687 BC–1600 AD
Matsushita (1956)	18	Japan	620–1909 AD
Basurah (2006)	18	Arabia, northern Africa, Spain	800–1600 AD
This study	21	Anatolia, Constantinople	1–1453 AD
This study	40	Middle East	1–1453 AD

piled by Frobesius (1739), Mairan (1754), Schøning (1758), Boué (1856), Wolf (1857), Lovering (1868), Fritz (1873), and Seydl (1954).

Vaquero et al. (2010) presented a set of auroral observations by Francisco Salva Campillo, who recorded in Barcelona during 1780–1825. This catalog represents a sudden drop in the number of annual auroral observations at about 1793 owing to the secular minimum in solar activity (Vaquero et al., 2010). Scafetta and Willson (2013) studied the historical Hungarian auroral records covering 438 years. They found that the maxima of the auroral observations comply with the maxima in the sunspot records and that there is a positive correlation between the auroral records and the solar activities.

Neuhäuser and Neuhäuser (2015) implemented five criteria of likeliness for aurora catalogs as night-time (darkness, sunset, sunrise), non-southern directions (northern, NE, NW, E–W, W–E), color (red, reddish, fiery, bloody, green, black), dynamics (fire, fiery), and repetition. However, these criteria directly contradicted auroral behavior during the extreme space weather events, as overhead aurora can extend down to $\sim 25°$ in magnetic latitude (vs. 40–50° in Anatolia) and the whitish aurora appears more on the equatorial side (Kimball, 1960; Kataoka and Iwahashi, 2017; Kataoka et al., 2019; Kataoka and Kazama, 2019). Indeed, Stephenson et al. (2019) rejected these criteria and their analyses on the basis of multiple counter-examples during the extreme space weather events and confirmed an enhanced solar activity around this epoch. Recently, such candidate records of mid-latitude aurorae have been intensively investigated (e.g., Usoskin et al., 2013; Stephenson, 2015), due to the discovery of footprints of an extreme solar particle storm in the cosmogenic isotopes around 774/775 (Miyake et al., 2012; Usoskin et al., 2013; Mekhaldi et al., 2015). Their conclusion is consistent with the isotope evidence for the extreme solar particle storm such as the detected ratio of Be^{10} and Cl^{36} (Mekhaldi et al., 2015), latitudinal concentration of C^{14} concentration (Uusitalo et al., 2018), and coincidental spikes of the multiple cosmogenic isotopes in both hemispheres (Büntgen et al., 2018).

The goal of this study is to compile a historical aurora catalog based on the existing catalogs, in order to analyze the past solar activity during the Medieval period. This research may also contribute to the understanding of public perception of the historical auroras. Constantinople and Anatolia have only been peripherally discussed up to now with regard to auroral observations.

2 Historical aurora borealis catalog for Anatolia and Constantinople (hABcAC) in the Medieval period

A historical aurora catalog observed only in Anatolia and Constantinople during the Medieval period is propounded and collected from the Link (1962), Botley (1964), Baldwin (1969), Newton (1972), Stothers (1979), Eather (1980), Silverman (1998), Dall'Olmo (1979), Andreasyan (2000), Little (2007), Silverman (2006), and Neuhäuser and Neuhäuser (2015) resources. In this catalog, 21 different historical aurora observations recorded in Anatolia and Constantinople during the Medieval period are presented in Table 2. The location map of the historical aurora observations is given in Fig. 1 and summarized in Table 3. Another collected ancient aurora catalog consisting of 40 auroral observations is shown in Table 4 for the Middle East region during the same period using Islamic historical texts, Arabic chronicles, and other auroral records given in Table 1. These two catalogs are plotted in Fig. 2 and evaluated all together. The Middle East aurora records and hABcAC overlap through the Medieval period, especially between 1097 and 1129 (Fig. 3). Also, Chinese and European aurora observations are in harmony with each other in this period (Siscoe, 1980).

In this catalog, the first auroral observation was observed in Constantinople in 333. Stothers (1979) described these observations as a sky fire according to the works of Aurelius Victor (320–390), who was a historian and politician of the

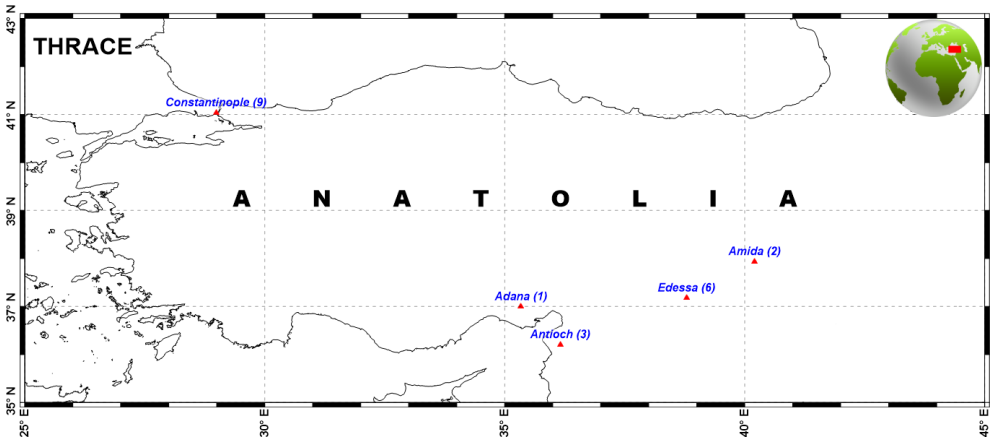

Figure 1. The location map of the historical aurora records during the Medieval period in Constantinople and Anatolia.

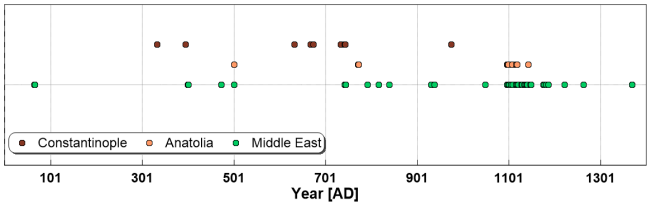

Figure 2. Plot of aurora observations recorded in the Constantinople, Anatolia, and Middle East regions.

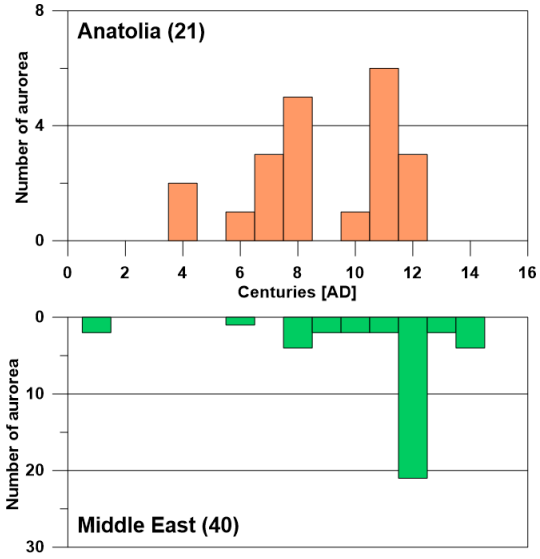

Figure 3. The number of aurora records per century observed in Constantinople, Anatolia, and the Middle East.

Roman Empire. On the other hand, Eather (1980) described an aurora observation over Constantinople in about 360 BC during the siege of Byzantium by Philip of Macedonia.

Little (2007) described an aurora observation record in Constantinople in 396: "A fiery cloud was observed from the East while the city darkened. At first, it was small, but later gradually grew and moved towards the city. At last, it terribly enlarged and poised over the entire city. A terrifying flame appeared to hang down. All people stacked to the church, and the place could not receive huge mass".

According to Link (1962) and Hayakawa et al. (2017), an aurora appeared in Asia Minor on 22 August 502, Thursday. This aurora was also observed in both Edessa (Botley, 1964) and Palestine after an earthquake (Russell, 1985) based on to the Chronicle of Joshua the Stylite and the Chronicle of Zuqnin. Joshua the Stylite described it: "On the 22 August this year, on the night preceding Friday, a great fire appeared to us blazing in the northern quarter all night. It was believed that the whole Earth was going to be devastated that night by a fire storm. However, the mercy of our Lord preserved us without damage". This appearance of the aurora borealis was also reported in Chronicon Edessenum without apocalyptic detail (Trombley and Watt, 2000).

According to the Historia Ecclesiastica of Ptolomaeus Lucensis there was an aurora sighting on a night of 633 in Constantinople (Dall'Olmo, 1979): "A bloody sign appearing just at that time was sighted. A bloodstained spear and a sharp light were observed on the sky for nearly all night". Theophanes (758/760–817), a Byzantine monk, theologian, and chronicler, reported an observation in the winter of 667: "There was a sign which appeared in the sky in the same winter". Theophanes reported another observation in 675–676: "This year a sign was seen in the sky on a Sabbath day" (Turtledove, 1982).

Theophanes recorded three aurora events for 734, 743 June, and 744 in Constantinople. The first aurora observation was reported in 734: "A fiery sign shining like a burning brand appeared in the sky in Constantinople". The second aurora observation was recorded by Theophanes in June of 743: "In the northern sky of Constantinople, a sign was observed in the month of June" (Turtledove, 1982). The last

Table 2. Historical aurora catalogs during the Medieval period used in this study.

No.	Date	Location	Description	References
1.	333	Constantinople	Sky fire.	Stothers (1979)
2.	396	Constantinople	A fiery cloud was seen from the east.	Little (2007)
3.	22 Aug 502, Thursday	Edessa	A great fire appeared to us blazing in the northern quarter the whole night.	Link (1962), Botley (1964), Hayakawa et al. (2017)
4.	633	Constantinople	A bloody spear and a light of the sky were sighted for nearly the all night.	Dall'Olmo (1979)
5.	668	Constantinople	There was a sign appeared in the sky in the same winter.	Turtledove (1982)
6.	675	Constantinople	In this year, a sign was seen in the sky on a Sabbath day.	Turtledove (1982)
7.	734	Constantinople	There was a sign in the sky which shone like a burning brand.	Turtledove (1982)
8.	Jun 743	Constantinople	In June, a sign appeared in the northern sky.	Turtledove (1982)
9.	744	Constantinople	This year, a sign appeared in the northern sky.	Turtledove (1982)
10.	771/772	Amida	Another sign appeared on the northern side.	Harrak (1999), Hayakawa et al. (2017)
11.	Jun 773, Friday	Amida	The sign that was seen a year ago in the northern region was seen again in this year, in the month of June, on a Friday.	Hayakawa et al. (2017), Harrak (1999)
12.	988	Constantinople	Frightened fiery pillars seen in the northern region for some nights.	Dall'Olmo (1979)
13.	21 Nov 1097, Monday	Edessa	A frightful and strange omen appeared in the northern portion of the sky.	Link (1962), Silverman (2006), Andreasyan (2000), Botley (1964)
14.	30 Dec 1097, Friday	Antioch	A very fabulous sign was watched in the sky.	Silverman (1998), Baldwin (1969), Botley (1964), Kery (1921)
15.	3 Jun 1098, Saturday	Antioch	A fiery red sky was seen.	Link (1962), Silverman (2006), Botley (1964)
16.	27 Sep 1098, Monday (10:00)	Edessa	A second omen appeared in the northern portion of the sky at the fourth hour of the night the sky flared up more than it had before and turned a deep red color.	Andreasyan (2000), Link (1962)
17.	27 Sep 1098, Monday	Antioch	Blaze of light girdled pole.	Link (1962), Botley (1964)
18.	1099	Edessa	A fire-like omen of a very deep red color appeared in the sky.	Andreasyan (2000), Link (1962), Silverman (2006)
19.	18 Nov 1100, Sunday	Edessa	The northern portion of the sky reddened, appearing more frightful and wondrous than the previous phenomenon.	Andreasyan (2000), Silverman (2006), Link (1962)
20.	1108	Adana	A light like the sunlight was seen in the middle of the night and remained about three hours in Djihan.	Chabot (1968), Dall'Olmo (1979)
21.	1 Apr 1143, Thursday	Edessa	A sign appeared in the sky from the north in the form of a luminous column	Andreasyan (2000)

Table 3. The number of historical aurora records observed in Constantinople and Anatolia.

No.	City	Latitude (° N)	Longitude (° E)	Numbers of observation
1.	Constantinople	41.03	28.99	9
2.	Edessa	37.17	38.79	6
3.	Amida	37.93	40.21	2
4.	Antioch	36.2	36.16	3
5.	Adana	36.99	35.34	1
Total				21

aurora record was observed in Constantinople for 744: "In the northern sky, a sign seemed this year, and dust fell in several places" (Turtledove, 1982; Neuhäuser and Neuhäuser, 2015).

Harrak (1999) and Hayakawa et al. (2017) listed two aurora records observed near Amida in the early 770s based on the Chronicle of Zuqnin. In the Chronicle of Zuqnin, the first observation was recorded in 771/772, Amida: "Another sign was seen on the northern side, and its view gave evidence of the menace of God against us. It appeared at reaping time, while wrapping the whole northern side of the sky from the western to eastern ends. It was look like a green sceptre, a red one, a yellow one, and a black one. It was ascending from the ground and changing into 70 shapes, while one sceptre was emerging and another disappearing". The second observation was recorded in the Chronicle of Zuqnin in 773, Amida: "In the month of June, on a Friday, another sign that was seen a year ago in the northern region was appeared again this year. It was on Fridays that it used to appear during these three consecutive years, stretching itself out from the eastern side to the western side. The sign would change into many shapes in such a way that as soon as a green ray vanished, a red one would appear, and as soon as the yellow one vanished, a green would appear, and as soon as this one vanished, a black one would appear" (Harrak, 1999). These two observations listed by Harrak (1999) based on the Chronicle of Zuqnin were also cited by Dall'Olmo (1979) according to the Chronique de Denys de Tell-Mahré (Chabot, 1895) with different dating. In Constantinople, another aurora observation was recorded in 988: "A luminous star and fiery pillars seen in the northern region of the sky for some nights. They frightened the people who saw them" (Dall'Olmo, 1979).

Matthew of Edessa, who wrote a chronicle, described the events that occurred between the years 952 and 1136 and reported four aurora observations around the year 1100 (Andreasyan, 2000). Matthew of Edessa reported the first aurora observation in the Armenian year 546 (25 February 1097–24 February 1098): "In this year, odd and horrible signs were observed on the northern side of the sky. No one had ever seen such an amazing omen so far. In the month of November, the sky kindled and reddened though the air was clear and quiet. The bloody sky was covered with stacks as if clustered on top of one another, becoming colorful. The stacks were set to slip through in an easterly direction, dispersed after having gathered, and enveloped the large amount of sky. Then, the dark redness of such an amazing degree reached up to the middle of the sky vault. The savants and sages interpreted this phenomenon as a sign of bloodshed. Actually, terrible events and disasters we included as a short story in our book were soon to be fulfilled".

Krey (1921) described an aurora observation during the siege of Antioch in the account of eyewitnesses and participants in the first crusade: "A great earthquake occurred on the third day before the Kalends of January (30 December 1097), and a very fabulous sign was noticed in the sky. The northern part of the sky was so red that it appeared as if the Sun rose to inform the day in the first sight of the night". This observation was also described by Baldwin (1969): "There was an earthquake on 30 December, and a frightening display of the aurora borealis next evening, and in this way God chastised his army, so that we were intent upon the light which was rising in the darkness, yet the minds of some were so blind and abandoned that they were recalled neither from luxury nor robbery. At this time the Bishop prescribed a fast of three days and urged prayers and alms, together with a procession, upon the people; moreover, he commanded the priests to devote themselves to masses and prayers, the clerics to psalms". On the other hand, another aurora was observed on 3 June 1098 at Antioch based on the Link (1962) catalog as a fiery red sky (Silverman, 2006).

Matthew of Edessa recorded a second aurora observation in the Armenian year 547 (25 February 1098–24 February 1099). "In the same year, a new sign appeared in the northern part of the sky. At the fourth hour of the night, the sky appeared more inflamed than before, and a dark red color. This phenomenon lasted from the evening until the fourth hour of the night. Such a terrible omen had never been seen so far. This omen rose gradually and covered the northern portion of the sky with the lines reaching the hills. All stars took on a fiery color. This phenomenon was an omen of rage and catastrophe" (Andreasyan, 2000). Botley (1964) reported an auroral observation in Antioch as a blaze of light girdled the pole. Link (1962) dated this observation to 27 September 1098.

In the Armenian year 548 (25 February 1099–24 February 1100) Matthew reported another aurora observation: "A fiery sign of dark red color appeared in the sky in this year. This omen heading from the northern to eastern parts of the sky appeared until the seventh hour of the night and then became black. It was said that this phenomenon was a sign of bloodshed of Christians. These predictions were truly realized. No favorable omen had appeared since the day when the Franks began their expedition. All omens, however, marked to realize the destruction, death, slaughter, famine and other diverse disasters" (Andreasyan, 2000).

Table 4. Ancient aurora observations recorded in the Middle East region during the Medieval period.

No.	Date	Place	Descriptions	References
1.	65	Jerusalem		Botley (1964)
2.	66	Jerusalem		Botley (1964)
3.	22 Aug 502	Palestine	A great fire appeared to us blazing in the northern quarter the whole night	Botley (1964)
4.	Jun 743	Syria	A mighty sign appeared in the heavens like columns of fire blazing in June	Chabot (1968)
5.	Sep 743	Middle East	Another sign appeared in September like a flame of fire and spread from the east to the west	Cook (2001)
6.	Jan 745	Middle East	In the middle of the sky, a large column of fire appeared during the night	Chabot (1968)
7.	11–17 May 793	Iraq	There occurred a violent wind and overshadowing of the heavens and a redness in the sky, on the night of Sunday	Basworth (1989)
8.	29 October 817	Iraq	A reddish glow appeared in the sky and stayed until late at night like two red columns	Basurah (2006)
9.	24 Sep 840	Middle East	A fiery cloud appeared in the northern part of the sky, moving from east to west.	Dall'Olmo (1979)
10.	9 Nov 931	Baghdad	An intense red glow appeared in the city of Al-Salam (Baghdad)	Basurah (2006)
11.	17 Oct 939	Syria	An intense red glow appeared in the atmosphere coming from north and west	Basurah (2006)
12.	5 Aug 1050	Middle East	Through which light shone out broad and glittering, and then became extinguished	Le Strange (1890)
13.	1097	Palestine		Botley (1964)
14.	1100	Palestine		Botley (1964)
15.	1102	Palestine		Botley (1964)
16.	1106	Syria		Botley (1964)
17.	1110	Syria		Botley (1964)
18.	16 Dec 1117	Palestine		Newton (1972), Botley (1964)
19.	1119	Armenia		Botley (1964)
20.	May 1121, Monday	Syria	There appeared a full arc, which had not been observed for many generations	Botley (1964)
21.	Jan 1129	Middle East	A fire appeared in the northern region. A sort of pillar was stretched toward the south.	Dall'Olmo (1979)
22.	Mar 1129	Middle East	A fire appeared in the northern region. A sort of pillar was stretched toward the south.	Dall'Olmo (1979)
23.	Apr 1129	Middle East	A fire appeared in the northern region. A sort of pillar was stretched toward the south.	Dall'Olmo (1979)
24.	Nov 1130	Middle East	A burning fire was seen in the northern region	Dall'Olmo (1979)
25.	21 Jul 1135	Middle East	A light like a torch moved from east to west. The light of the moon and of the stars was obscured. A frightful noise followed	Dall'Olmo (1979)

Table 4. Ancient aurora observations recorded in the Middle East region during the Medieval period.

No.	Date	Place	Descriptions	References
26.	Oct 1138	Syria	A red sign was seen in the northern part of the sky	Botley (1964)
27.	22 Jun 1140	Syria	Red lances were seen in the northern region.	Botley (1964)
28.	Aug 1141	Middle East	Rays of fire were observed in the northern region.	Dall'Olmo (1979)
29.	Sep 1141	Syria	A brightness as bright as the Sun broke out in the northeast. It shone as if the sky were on fire.	Botley (1964)
30.	1149	Syria		Botley (1964)
31.	1150	Palestine		Botley (1964)
32.	6 Sep–5 Oct 1176	Syria	An intense red light appeared in the sky from the east	Basurah (2006)
33.	7 May 1179	Syria	The sky became cloudy and pillars of fire appeared at the horizon	Basurah (2006)
34.	Jul 1187	Tiberias, Israel		Botley (1964)
35.	26 Oct 1223	Syria	We saw from Bani Helal Mountain (toward the northerly direction) a huge light over Gassune; we thought that Damascus was on fire.	Basurah (2006)
36.	20–30 Jul 1264	Syria	Bright glowing columns appeared toward the northwest	Basurah (2006)
37.	27 Nov 1370	Jerusalem	A great reddish glow appeared in the sky of Jerusalem	Basurah (2006)
38.	27 Nov 1370	Damascus	A great reddish glow appeared in the sky of Damascus	Basurah (2006)
39.	27 Nov 1370	Homs	A great reddish glow appeared in the sky of Homs	Basurah (2006)
40.	27 Nov 1370	Aleppo	A great reddish glow appeared in the sky of Aleppo	Basurah (2006)

Matthew recorded the last aurora observation in the Armenian year 549 (25 February 1100–24 February 1101): "The northern part of the sky flushed red for the fourth time in this year. The fiery red omen appeared more horrific than the previous one and subsequently changed into black. This fourth appearance coincided with a lunar eclipse. This phenomenon was a sign of the celestial wrath of God over the Christians as previously said by the prophet Jeremiah with these words: His wrath will blaze up from the northern part of the sky. Indeed, several misfortunes occurred as we never could have expected" (Andreasyan, 2000).

Dall'Olmo (1979) reported an aurora observation based on the Chronicle of Michael the Syrian translated into French by Chabot (1968): "In the year 1108, a light like the sunlight was seen in the middle of the night, and remained about three hours in the Djihan region near Adana". Dall'Olmo (1979) also cited 12 auroral records observed probably in the Middle East from 745 to 1141 (Table 4) according to the Chronicle of Michael the Syrian (Chabot, 1968).

Priest Grigor, who continued Matthew's Chronicle and recorded events for the years 1136/1137–1162/1163, added one aurora observation in about the year 1143. In the Armenian year 592 (14 February 1143–13 February 1144) Priest Grigor described the aurora observation: "On Holy Thursday (1 April 1143), an omen forming a luminous column appeared in the northern portion of the sky. This omen was visible for eight days. Three sovereigns died after the appearance of this phenomenon" (Andreasyan, 2000).

3 Results and discussions

The main purpose of this study is to present an aurora catalog for Constantinople and Anatolia during the Medieval period based on the existing catalogs. Twenty-one different historical aurora records are presented for Constantinople and Anatolia during the Medieval period (Table 2). Another aurora catalog containing 40 records collected from different sources is also given (Le Strange, 1890; Link, 1962; Botley, 1964; Newton, 1972; Dall'Olmo, 1979; Silverman, 1998; Basurah, 2006) for the Middle East region (Table 4). The aurorae were generally seen in the northern and eastern parts of the sky. The colors of the aurora observations were red, green, yellow, and black depending on the height and relative concentrations of the nitrogen and oxygen compounds in the atmosphere (Eather, 1980).

The aurora records strongly correlated with high solar activity (Siscoe, 1980) provide some information about the Sun–Earth interaction as previously proved by

Scafetta (2012). Stronger solar dynamics were realized in aurorae with colors green–yellow–red as seen in 772 and 773 in Amida. The low-latitude aurorae of 772–773 are interesting, being very close to the extreme solar event of 774/775 (Miyake et al., 2012; Usoskin et al., 2013; Mekhaldi et al., 2015). Miyake et al. (2012) and Usoskin et al. (2013) confirmed the 770s high solar events presenting ^{14}C measurements from the annual rings of cedar trees in Japan and an inappropriate carbon cycle model in German oak, respectively. These low-latitude aurorae are quite close to the extreme solar particle storm in 774/775 and support not the solar minimum (Neuhäuser and Neuhäuser, 2015), but high solar activity (Usoskin et al., 2013; Mekhaldi et al., 2015; Stephenson et al., 2019). The auroral records have also proven themselves to be a valuable data source for the investigation of the secular variation of solar activity.

Paleomagnetic researches demonstrate that the recent dipole strength was nearly 50 % weaker than it was 2500 years ago (Raspopov et al., 2003). Siscoe and Siebert (2002) indicated that the dipole strength was 1.5 times as large as that of the present value. The position of the geomagnetic latitude and dipole moment might be the reason for observing aurorae in Constantinople and Anatolia so frequently. The average dipole moments for 750 and 1250 are 8.85×10^{22} and 8.90×10^{22} Am^2, slightly higher than the present value of 7.78×10^{22} Am^2 (Korte and Constable, 2005; Gallet et al., 2005). According to the Kawai et al. (1965) the axis of the geomagnetic dipole could have inclined towards Asia at around the 11th–12th centuries. In addition, the possibility of auroral occurrence at low latitudes could demonstrate changes in the location of the North Magnetic Pole (Silverman, 1998).

The position of the magnetic poles is the most important factor defining whether the aurora was observed in a geographic region. Palaeomagnetic data provide similar longitude values (85° N, 115° E) for the North Magnetic Pole (Merrill and McElhinny, 1983). The positions of the North Magnetic Pole have changed from 10 to 358° N in longitude and from 79 to 88° E in latitude over the past 2500 years (Ohno and Hamano, 1992). During the interval of 1127–1129, the North Magnetic Pole was located at a geographic latitude of 80° N and geographic longitudes including East Asia (Merrill and McElhinny, 1983; Constable et al., 2000). According to Fukushima (1994), the North Magnetic Pole was located at 81° N in the Eastern Hemisphere near East Asia (100 to 130° E) in the Medieval period. The North Magnetic Poles of the dipole axis computed from the average spherical harmonic models were 84.8° N and 103.8° E in 1100 (Constable et al., 2000).

The geomagnetic latitude of Amida in the late 8th century was about 50.1° N (Neuhäuser and Neuhäuser, 2015) based on the Holocene geomagnetic field (Nilsson et al., 2014) and 45° N (Hayakawa et al., 2017) based on the location of the North Magnetic Pole over the past 2000 years (Merrill and McElhinny, 1983). According to Silverman (2006), the geomagnetic latitudes of Edessa and Antioch were 41° N and 40° N, respectively. Strong geomagnetic storms, indicating strong solar activity around 770 and 1100, should have existed in Amida (45° N), Edessa (41° N), and Antioch (40° N).

Bekli et al. (2017) demonstrated that the naked eye sunspot observations from 974 to 1278 and aurora records from 965 to 1273 show multiple unusual peaks related to the high solar activity at latitudes below 45° N by using Chinese and Korean historical sources. The high aurora activity events associated with great magnetic storms occurred around the maximum phase of solar cycles rather than around the minimum (Kataoka et al., 2017). Vaquero and Trigo (2012) stated the period from 1095 to 1204 as an average solar cycle length, whereas this needs to be carefully compared with the reconstructed solar cycles on the basis of cosmogenic isotopes (Miyahara et al., 2008; Kataoka et al., 2017). Nevertheless, this period is characterized by numerous records of sunspots and aurorae shown in Vaquero and Vazquez (2009) and supported by Anatolian reports compiled in this article. This is highly consistent with an appearance of a gigantic sunspot in 1128 that caused a serious geomagnetic storm (Willis and Stephenson, 2001).

In the Medieval period, people thought that the aurora was a sign of the anger of God, menace, threat, apocalyptic, doomsday, misfortunes, war, slaughter, and bloodshed. Little (2007) described an aurora observation record in Constantinople in 396: "All people stacked to the church, and the place could not receive huge mass. But after that great tribulation, when God had accredited His word, the cloud began to diminish and at last disappeared. The people, freed from fear for a while, again heard that they must migrate, because the whole city would be destroyed on the next Sabbath. The whole people left the city with the Emperor; no one remained in his house. The city was saved. What shall we say? adds Augustine. Was this the anger of God or rather His mercy"?

In the Chronicle of Zuqnin, an aurora observation recorded in 772 in Amida was described: "Another sign was seen on the northern side, and its view gave evidence about the menace of God against us. For the intelligent person the sign indicated menace. Many people said many things about it; some said it announced bloodshed, and others said other things. But who knows the deeds of the Lord"?

Matthew of Edessa described the aurora phenomenon as a sign of rage, catastrophe, and celestial wrath of God over the Christians and bloodshed of Christians. Matthew of Edessa reported that "These predictions were truly realized. No favorable omen had appeared since the day when the Franks began their expedition. All omens noticed to realize destruction, death, slaughter, famine and other diverse disasters" (Andreasyan, 2000).

4 Conclusions

This study establishing solar activity during the Medieval period reports on the aurora observations recorded in the Constantinople, Anatolia, and Middle East regions. The following conclusions can be summarized.

1. A historical aurora catalog for Constantinople and Anatolia (hABcAC) containing 21 different aurora records provides important information on variations in the geomagnetic field and auroral activity during the Medieval period.

2. The solar activity, intensity of dipole moment, and position of the North Magnetic Pole might be the most important factors observing aurorae in the Constantinople, Anatolia, and Middle East regions.

3. The historical aurora catalogs exceptionally promote that there is a remarkable correlation between the past solar activity and aurora.

4. In Constantinople, Anatolia, and the Middle East, there was relatively high auroral activity during the years around 1100, which is quite consistent with the naked-eye sunspot observations related to solar activity as stated by Vaquero et al. (2002) and Bekli et al. (2017).

5. People believed that the aurora was a sign of the celestial wrath of God, menace, threat, apocalyptic, doomsday, misfortunes, war, slaughter, rage, catastrophe, and bloodshed.

6. The high and low auroral events associated with solar activity variations provide substantial use of knowledge to design and alleviate space weather hazards in future.

Data availability. The data used in this study can be obtained by contacting the corresponding author.

Competing interests. The author declares that there is no conflict of interest.

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