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An Optical Atmospheric Phenomenon Observed in 1670 over the City of Astrakhan Was Not a Mid-Latitude Aurora

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Abstract It has recently been claimed (Zolotova and Ponyavin *Solar Phys.*, **291**, 2869, 2016; ZP16 henceforth) that a mid-latitude optical phenomenon, which took place over the city of Astrakhan in July 1670, according to Russian chronicles, were a strong aurora borealis. If this were true, it would imply a very strong or even severe geomagnetic storm during the quietest part of the Maunder minimum. However, as we argue in this article, this conclusion is erroneous and caused by a misinterpretation of the chronicle record. As a result of a thorough analysis of the chronicle text, we show that the described phenomenon occurred during the daylight period of the day ("the last morning hour"), in the south ("towards noon"), and its description does not match that of an aurora. The date of the event was also interpreted incorrectly. We conclude that this phenomenon was not a mid-latitude aurora, but an atmospheric phenomenon, the so-called sundog (or parhelion), which is a particular type of solar halo. Accordingly, the claim of a strong mid-latitude aurora during the deep Maunder Minimum is not correct and should be dismissed.

Keywords Solar activity · Sunspots · Solar observations · Solar cycle

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1. Introduction

The period of extremely low solar activity that took place during the second half of the seventeenth century and lasted until the beginning of the eighteenth century (1645 – 1715) is called the Maunder Minimum (MM). It has been the subject of numerous investigations since it poses an important observational constraint on the centennial evolution of solar activity (*e.g.* Sokoloff, 2004; Charbonneau, 2010). Although the existence of the MM is well known (*e.g.* Eddy, 1976, 1983), the exact level of activity during this period is still discussed as new data are revealed and some old data are revisited (Vaquero and Trigo, 2014; Vaquero *et al.*, 2011, 2015; Usoskin *et al.*, 2015; Svalgaard and Schatten, 2016). Very recent estimates of the level of solar activity during the MM based on a revision of historical sunspot observations clearly imply very low values (Carrasco, Álvarez, and Vaquero, 2015; Carrasco and Vaquero, 2016; Usoskin *et al.*, 2015; Vaquero *et al.*, 2016). We note that a claim of a moderate level of solar activity during the MM (Zolotova and Ponyavin, 2015) was caused by misinterpretation of the data, as shown by Usoskin *et al.* (2015). Moreover, the existence of the MM and other similar grand minima of solar activity, which form a special quiet mode of the solar dynamo, is independently confirmed by cosmogenic isotope data for the last millennia (*e.g.* Beer, McCracken, and von Steiger, 2012; Steinhilber *et al.*, 2012; Inceoglu *et al.*, 2015; Usoskin *et al.*, 2014, 2016).

There are some records of auroras observed during the MM (*e.g.* Letfus, 2000), but all the European records are related to high geomagnetic latitudes where auroras occur regularly (the auroral oval) even without geomagnetic storms and sunspots (Vázquez *et al.*, 2016; Usoskin *et al.*, 2015). On the other hand, there are also records from Korean chronicles that may be interpreted as auroras (Zhang, 1985; Lee *et al.*, 2004). However, as noticed by Zhang (1985), most of these events were observed in the southern direction, which contradicts the data from neighboring China and Japan. Accordingly, the nature of these records is still debated (see discussion in Vázquez *et al.*, 2016).

A new result of the reanalysis of some data for the period of the MM has been published recently by Zolotova and Ponyavin (2016, ZP16 henceforth), who stated in particular that a strong mid-latitude aurora was observed in the summer of 1670, *i.e.* during the deep phase of the MM:

> *"The Mazurinsky chronicler Peter Zolotarev (Buganov and Rybakov, 1968) described the observations of meteors by the Astrakhan guard of archers on 13 July 7178 (the year since the creation of the world, which means 1670) and auroral observations ("three pillars of different colors, like the heavenly arc in the cloud, and crowns of many colors on top" as translated by us) of the same guard (July – August 1670, according to Loysha, Krakovetsky, and Popov, 1989). Astrakhan is a Russian city located at latitude* 46°*, which means a strong geomagnetic storm and appearance of a large activity complex on the Sun."*

The aurora discussed by ZP16 would have appeared at mid-latitude at $\approx 46°$ geographic latitude. In 1670, this location had a geomagnetic latitude of $\approx 49°$ using the archeomagnetic model (Licht *et al.*, 2013). If confirmed, this would imply a strong geomagnetic storm during the deep phase of the MM and would lead to a need to revisit our paradigm of the extremely quiet Sun during that time. However, as we argue in this article, this claim by ZP16 was caused by a misinterpretation of the original chronicle record written in seventeenth-century Russian. With a careful analysis of the chronicle and other historical sources, we show that the event in question cannot have been an aurora borealis, but rather was a day-time optical atmospheric phenomenon, and accordingly the claim by ZP16 should be dismissed.

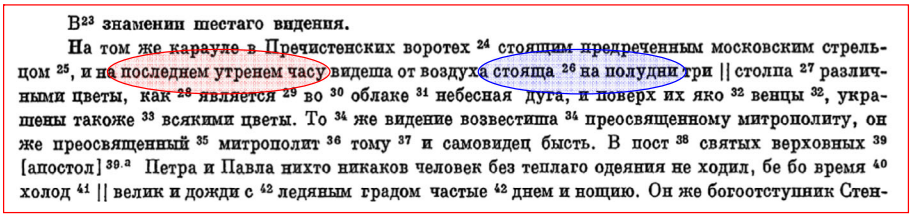
В[23] знамении шестаго видения.
На том же карауле в Пречистенских воротех [24] стоящим предреченным московским стрельцом [25], и на последнем утренем часу видеша от воздуха стояща [26] на полудни три || столпа [27] различными цветы, как [28] является [29] во [30] облаке [31] небесная дуга, и поверх их яко [32] венцы [32], украшены такоже [33] всякими цветы. То [34] же видение возвестиша [34] преосвященному митрополиту, он же преосвященный [35] митрополит [36] тому [37] и самовидец бысть. В пост [38] святых верховных [39] [апостол] [39.a] Петра и Павла нихто никаков человек без теплаго одеяния не ходил, бе бо время [40] холод [41] || велик и дожди с [42] ледяным градом частые [42] днем и нощию. Он же богоотступник Стен-

Figure 1 A scan of the record related to the discussed phenomenon, from page 212 of Buganov and Rybakov (1968). The red and blue shadings mark the direct mentioning of the time and direction of the phenomenon; both were missing in the translation of ZP16.

2. The Original Chronicle

The original record referred to by ZP16 appears in the writing of Piotr Zolotarev, an eyewitness and a chronicler of the Astrakhan region during the period of the open rebelion led by famous Stepan Razin (Buganov and Rybakov, 1968).[1] ZP16 erroneously called him "Mazurinsky chronicler", confusing him with another source in the book by Buganov and Rybakov (1968). We note that this chronicle is known since the mid-nineteenth century (*e.g.* Kostomarov, 1994)[2] and forms the main source of information about the period around 1670 when Razin and his troops conquered the great city of Astrakhan on 22 June[3] 1670. Since the city of Astrakhan was expecting assault, the citizens and defenders paid particular attention to unusual events that were considered as omens. In particular, during 1669 – 1670, when the rebels were approaching Astrakhan, several omens were reported. Some of them were clearly related to earthquakes, unusual noise, and meteor showers, but the sixth omen was interpreted by ZP16 as an aurora.

We note that the translation of the original chronicle record about this sixth omen, as provided by ZP16 *("three pillars of different colors, like the heavenly arc in the cloud, and crowns of many colors on top")* is incomplete and misleading. The relevant part of the chronicle record, directly reproducing the original text, is shown in Figure 1. Its translation into English was made by us as shown below (the order of words was changed to correspond to English):

> The omen of the sixth apparition.
> *Moscovite streltsy* (regular type of soldiers armed with rifles) standing in the same guard in the Prechistensky Gate, and **in the last morning hour**, saw in the air, **standing at [the direction of the] noon**, *three pillars of different colors, as appears in a cloud a heavenly arch, and above them, something like crowns, also decorated in various colors.* This apparition was announced to the Metropolitan bishop, who was also an eyewitness of this. During the feast of the supreme saints (apostles) Peter and Paul,[4] no one was walking without warm clothes, because there often were, during that time, great cold and rains with ice hail during day and night.

[1] See reference R1 in the electronic supplementary material (ESM) for the original source.

[2] See reference R2 in the ESM for the original source.

[3] The dates are given according to the Julian calendar (JD) used during that time. The difference between the JD and the GD (Gregorian date) was 10 days in 1760, so that 20 June 1760 in JD corresponds to 30 June 1760 in GD.

[4] The feast of Peter and Paul lasted from 04 June until 11 July 1670.

The text of the record provided by ZP16 is denoted by italics in the translation above. This clearly relates only to a description of the optical phenomenon. The important facts mentioned in the original record (see Figure 1) but not mentioned by ZP16 are denoted in boldface and are related to the timing and direction of the phenomenon. The second part of the record describes the unusual meteorological conditions during that time. In the subsequent sections we analyze this information in full detail.

2.1. Direction

At such low latitude, auroras, if they appear, are observed usually in the northern direction. While ZP16 did not mentioned this in their study, the original record (Figure 1) provides a clear information about the direction of the phenomenon (*standing at [in the direction of the] noon*). The direction of noon unambiguously means south. This was also noted by Kostomarov (1994), who wrote "In the southern sky, three pillars were sparkling with rainbow colors...". Thus, the phenomenon was seen in the south.

2.2. Date of the Event

Although it is not important for the discussion of the origin of the phenomenon, it is interesting to note that the date of the event in the chronicle and in ZP16 is not correct. According to Buganov and Rybakov (1968), the fifth omen was seen on 13 July, and the sixth omen after that, in July – August 1670, as cited by ZP16. However, this cannot be true because the rebels had conquered the city of Astrakhan during the night of 21 to 22 June 1670, and there were no muscovite guards in the city after that. Most likely, this incorrect date was due to a typo (the record date of 13 July should be 13 June, as mentioned in footnote 38 on page 212 of Buganov and Rybakov, 1968). This error has been corrected by Kostomarov (1994) and Schperk (1895).[5] On the other hand, the next record in the chronicle is dated 19 June 1670. Accordingly, the phenomenon in question took place between 14 – 19 June 1670.

We have checked that this period corresponded to the bright Moon phase between the first quarter on 15 June and the full Moon on 24 June 1670, making an aurora observation even more problematic.

We note that no other catalog gives any hint of an aurora in late June 1670.

2.3. Timing of the Event

Since an aurora is a faint phenomenon, it is important for a correct interpretation of the chronicle record, that it is visible only during the night and not during daylight times. The exact timing of the event, *i.e.* the time of the day when the phenomenon was observed, was not mentioned and discussed by ZP16. However, the original record does give information on this, saying that the phenomenon was observed *"in the last morning hour"*. This note is, however, somewhat ambiguous since the term "morning" is not well defined for that time and may vary depending on the context. At that time, the division of a day into parts was not related to hours on a clock as today, but was linked to the position of the Sun (sunrise, noon, sunset).

Since the phenomenon was likely to occur in mid- to late-June (see Section 2.2), we consider the timing for 19 June 1670. Daylight (sunrise to sunset) was from 04:11 – 19:55 local

[5] See reference R3 in the ESM for the original source.

time, while the full dark night was short, from 23:31 – 02:07 local time, with the twilight between them.

Considering a typical definition of the morning as lasting between sunrise and noon, "the last morning hour" would be between 11:00 and noon local time, thus, when the Sun is high. However, this definition may not have been used by this particular chronicler. To ensure that the word "morning" is not applicable to the dark or even twilight period, *i.e.* before sunrise, we checked the entire chronicle by the same author for mentions of the hours of the day. Relevant examples mentioning morning hours and sunrise are shown below.

The text on page 208 of Buganov and Rybakov (1968) reads (see Figure S1 in the electronic supplementary material, ESM): "In January, day four, *an hour before light*, on the day of Saturday, there was an earthquake". The same term was also used in another place on the same page. This suggests that darkness or twilight before sunrise was not regarded as morning, but was denoted differently by this chronicler.

The text on page 209 (see Figure S1 in the ESM), regarding the fourth omen (dated in 1669), reads: "In July, day 19, there was another earthquake, stronger than that, *in the morning, at the end of the first hour*." Here the term "morning" is used explicitly.

The text on page 211 (Figure S3 in the ESM) says about the fifth omen:

> "In July,[6] day 13, in the city's Kremlin, muscovite streltsy of Alexeev of the order of Solovtsov were stood in the guard in the Prechistenskie Gate ... *for three hours before light* and saw an omen that the sky opened over all of Astrakhan and spilled over the entire city like furnace sparks. And of that omen, the streltsy, when coming back from the guard to the cathedral, told the Metropolitan bishop Ioseph... The bishop, hearing this, was in tears for long hours, and, when he returned to the cell, said "This apparition is such – spills from heaven the vial of God's anger", and *in the morning*, [he] told [this] to the boyar and voivode duke Ivan Semenovich Prozorovsky and his comrades."

Neglecting details, we consider only the timing of the events described here. The guards saw (presumably) a meteor shower *three hours before light* (*i.e.* before sunrise). After this, they finished their guard shift, returned, and reported this to the bishop, who first cried for a long time, then went to his cell to think this omen over, and only after that, *in the morning*, told others about this. It is quite clear that the term *morning* is different from *before light* here and denotes a later time.

The text on page 227 (Figure S4 in the ESM) tells about the murder of the Metropolitan bishop Ioseph on 11 May 1671: "*In the morning, in the sixth hour of the day*, they ordered to ring the great bell, not fast..". In this record, there is a clear connection of the term "morning" to the clock, *i.e.* the sixth hour of the day, which was, according to the chronicle, 11 May 1671. Sunrise for that day was at 04:15 local time, implying that the sixth hour of the day was well during sunlight.

From the analysis presented above we conclude that the time mentioned as *the last morning hour* unambiguously corresponds to full daylight, which is the time after sunrise, most likely closer to noon, which makes it impossible to see an aurora, but is appropriate for other atmospheric phenomena.

[6]The month is a typo, it should be June, see Section 2.2.

3. The Origin of the Phenomenon

3.1. Could It Be an Aurora?

We have shown in the previous section that the phenomenon took place during the daylight period of a day and toward the south, which makes it hardly possible that it was an aurora. There are additional arguments dismissing an interpretation of the phenomenon as an aurora.

First, if observed in Astrakhan, the aurora must have been seen across populated areas in North and Central Europe, North America, northern China, Japan, and of course throughout the entire Russia. However, we are not aware of any other independent report confirming such an event (*e.g.* Vázquez *et al.*, 2016). We note that according to Schperk (1895), there is only one clear confirmed observation of an aurora in Astrakhan, which took place on 23 January 1872 (see page 381 there).

Second, the description of the phenomenon (Figure 1 and its description) includes three pillars with crown-like heads characterized by rainbow colors. We note that this description does not match that of an aurora, since rainbow colors cannot be produced in an aurora, although a combination of green and red might be described as "rainbow like".

Thus, from the very description of the phenomenon it follows that it is unlikely to be an aurora. Although historical writings may be very imprecise, in combination with the available information on the timing and direction of the phenomenon, we have solid grounds to exclude an auroral origin of the phenomenon.

3.2. What Could It Be?

We make an educated guess at what such a phenomenon could be.

First, we note that such optical phenomena are not rare in the city of Astrakhan, which is located so that to its south lies the Caspian sea and a large salt marsh. As stated by Schperk (1895) (see the highlighted text in Figure S5 in the ESM), "In the same year [1670], light pillars were repeatedly observed in the sky." Although some following descriptions are related to other phenomena, like ball-lightning, the event of 16 March [1848] describes a similar phenomenon: ".. at 7 in the evening, in the southwest and northeast parts of the sky, fiery pillars were observed, two in the southwest part of the sky, three in the northeast, which gradually disappeared after two hours."

Most likely, the phenomenon observed was an atmospheric optical phenomenon called sundog (known also as mock suns or parhelia), which is a specific type of solar halo caused by refraction of sunlight on planar hexagonal ice crystals, which exist either in clouds or, during cold weather, float in the near-ground air, where they form an icy haze or "diamond dust" (*e.g.* Greenler, 1990). The refraction of sunlight leads to the appearance of two "pseudo-suns" located at 22° to the right and left of the true Sun. In hazy conditions, the three suns often appear as pillars with rainbow color separation. An example of a clear sundog appearance is shown in Figure 2.

We note that the weather was very cold in June 1670 (see Figure 1 and its discussion). Thus, we conclude that the description and conditions of the occurrence of the event matches the sundog phenomenon, which is expected to appear in the direction of the Sun, south in this case (Section 2.1). Of course, this is only a speculation that cannot prove the origin of the phenomenon, and this is not the objective of this work.

Figure 2 An example of a sundog phenomenon (Fargo, North Dakota, on 18 February 2009, taken from Wikipedia, https://en.wikipedia.org/wiki/Sun_dogs).

4. Discussion and Conclusions

We have shown that the event, claimed by ZP16 to be an aurora observed in the city of Astrakhan in the summer of 1670, according to a Russian chronicle (Buganov and Rybakov, 1968) could not be an aurora borealis. A thorough analysis of the original text of the chronicle unambiguously implies that the reported event was observed during daylight time (likely late morning before noon) and toward the south, which dismisses the aurora interpretation. Neither was it confirmed from other independent sources. We propose that it was likely a complex optical atmospheric phenomenon, including parhelia and three light pillars

We emphasize that the record analyzed here was not made in a scientific manner, but was rather based on a compilation made by a chronicler who was not specifically interested in scientific scrupulousness. In this particular case, we were fortunate to find clear evidence that proved that this event was not an aurora, but even though the description was indistinct, information obtained from amateurs, especially if not from the actual observers, should be very carefully considered when confronted with regular and scientific observations by professional astronomers, as was done by the Paris school of astronomy for the period of the Maunder minimum (Ribes and Nesme-Ribes, 1993).

To conclude, the claim of Zolotova and Ponyavin (2016) that a strong geomagnetic storm and a "large activity complex on the Sun" appeared in 1670, *i.e.* during the deep Maunder minimum, should be dismissed as based on a misinterpretation of the original historical record. Thus, there is currently no evidence of high geomagnetic or solar activity during the Maunder minimum.

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