JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, A08230, doi:10.1029/2007JA012943, 2008

The 1870 space weather event: Geomagnetic and auroral records

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Received 15 November 2007; revised 9 April 2008; accepted 15 May 2008; published 28 August 2008.

[1] The great solar storm that took place on 24–25 October 1870 is not well known and has been almost absent from previous studies. In this work, a large amount of information that was registered at the time is compiled and analyzed, including early geomagnetic data and several comprehensive descriptions of the auroras observed during these two nights. These descriptions reveal unusual characteristics for a typical low-latitude aurora. For example, unlike most low-latitude auroras (generally red and diffuse), this event was mostly characterized by a variable palette of colors, including greenish and white. The geomagnetic records analyzed from Lisbon and Coimbra (Portugal), Greenwich (United Kingdom), Munich (Germany), and Helsinki (Finland) clearly show an intense geomagnetic disturbance on 24–25 October. The Coimbra magnetograms reveal that this disturbance consisted of two distinct geomagnetic storms, the first on 24 October (with amplitudes of 37′ in D and 182 nT and 48 nT in H and Z, respectively), and the second on 25 October (with amplitudes of 33′ in D and 281 nT and 192 nT in H and Z, respectively). Finally, from early photographic solar observations made during 1870, we have identified a long-lived group of sunspots that are most likely related to the solar source of this great event of space weather.

Citation: Vaquero, J. M., M. A. Valente, R. M. Trigo, P. Ribeiro, and M. C. Gallego (2008), The 1870 space weather event: Geomagnetic and auroral records, *J. Geophys. Res.*, *113*, A08230, doi:10.1029/2007JA012943.

1. Introduction

[2] It is known that the appearance of auroras at lower latitudes is associated with intense eruptive flares and their associated coronal mass ejections (CMEs). These low-latitude auroras and their associated geomagnetic storms can disturb power grid networks and pose large risks to spacecrafts and high radiation hazards to astronauts in orbit. The U.S. agency National Oceanic and Atmospheric Administration (NOAA) has developed the Space Weather Scales to improve understanding of space weather events among technical operators and the general public alike. The Scales project allows correlating space weather events with their likely effects on technological systems [*Poppe*, 2000]. Fortunately, recent developments in solar monitoring satellites (e.g., SOHO, Coriolis) have shown their ability to predict the timing for the arrival to Earth of solar flares and/or CMEs, a fact that can be of the outmost importance to protect spacecrafts, power grids and humans in space [*Baker*, 2000; *Wu et al.*, 2000]. In any case, it should be stressed that the study of these intense events in the past can help to put the recent occurrence of intense solar storms, such as those that have occurred in October–November 2003, into a wider perspective.

[3] The study of the largest geomagnetic storms that have occurred in the last two centuries is of relevance today because it provides additional information on extremely damaging space weather events that can strike in the near future [*Lanzerotti*, 2007]. Some important space weather events have been studied in detail in recent years, such as the historical events that have occurred on 2 September 1859 [*Cliver*, 2006; *Tsurutani et al.*, 2003], 25 September 1909 [*Silverman*, 1995], 14–15 May 1921 [*Silverman and Cliver*, 2001], and 25 January 1938 [*Barlow*, 1938; *Botley*, 1938; *Bernhard*, 1938; *Hess et al.*, 1938]. Other, more recent, space weather events have already occurred with scientific satellites orbiting the Earth, providing a wealth of information impossible to attain prior to the 1960s. These include the episodes on 4–5 August 1972 [*McKinnon and members of the Space Environment Services Center*, 1972; *McIntosh*, 1972; *Rust*, 1972], 13–14 March 1989 [*Allen et al.*, 1989; *Livesey*, 1990],and the recent October–November 2003 [*Veselovsky et al.*, 2004] event. The exact dates for other important geomagnetic/solar storms that occurred between 1850 and 1950 are relatively well known. However, some of the remaining "presatellite" episodes have never been analyzed in detail. This may be due to the fact that there is insufficient information on those episodes, or because, despite the existence of data, this is scattered throughout too many different sources, and few research groups have been interested in spending their time and

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0148-0227/08/2007JA012943$09.00

Table 1. Selected Sample of Places of Interest Where the Aurora Was Observed or the Geomagnetic Field Measured During the 1870 Space Weather Event, Including the Geographical Coordinates and Geomagnetic Latitude at That Time[a]

	Geographical Coordinates			
Place	Latitude (°N)	Longitude (°E)	Geomagnetic Latitude (°N)	Reference
London	51.50	359.87	51.0	*Jones* [1955]
Tours	47.38	0.68	47.0	*Fron* [1870]
Santander	43.45	356.20	44.2	*Fuertes Acevedo* [1876]
New York	40.75	286.02	58.3	*Silverman* [2008a]
Coimbra	40.22	351.58	42.2	This work
Lisbon	38.70	350.87	40.9	This work
Athens	**37.98**	**23.72**	**33.4**	***Carapiperis* [1956]**
Baghdad	**33.32**	**44.38**	**26.4**	***Silverman* [2008a]**
Cairo	**30.05**	**31.23**	**23.4**	***Silverman* [2008a]**
Natal	−28.93	30.82	−38.5	*Jones* [1955]

[a]Low geomagnetic locations are highlighted in bold.

resources to merge and provide a comprehensive description of such events.

[4] In this sense, the event that occurred during 24–25 October 1870 represents a very interesting example. This episode does not appear in the different "rankings" of the most important events in *Cliver and Svalgaard* [2004]. In fact, this storm appears only ranked number 61 in the list of major magnetic storms using the *AA** index (see http://www.ngdc.noaa.gov/stp/GEOMAG/aastar.shtml). However, this event belongs to both selected groups of (1) auroras with a maximum equatorward extension, about 11° closer to the equator than the majority of auroras, and auroras observed at low latitudes and (2) less well-documented auroras [*Silverman*, 2006]. Some places (including all the low-latitude sites) where the aurora was observed are listed in Table 1. Moreover, seven auroras observed within 30° of the geomagnetic equator reported during the period 1859–1958 are listed in Table 2.

[5] Furthermore some authors rank this intense auroral display within the top tier of the 19th century auroras, close to 1859 and 1872 [*Bone*, 2007]. In fact this unusual low-latitude aurora had a significant impact at the educated society of the 1870s as it can be easily verified by several descriptions of the phenomena in the most respected newspapers of that year, namely, the *London Times* and the *New York Times*.

[6] Figure 1 shows the *aa* and *Aa* global geomagnetic indices around this event although we must note that there is growing evidence that the *aa* index is too low, 3 nT approximately, for years before 1957 [*Svalgaard and Cliver*, 2007]. The first features are associated with relatively minor peaks that have occurred on 14 and 20 October, but these are dwarfed when compared to the large peaks that can be observed during the days 24 and 25 in both indices. Among other issues, it would be particularly appealing to be able to identify the source of this geomagnetic perturbation. Monthly sunspot numbers covering solar cycle 11 (1866–1880) are shown in Figure 2 (top). For the year 1870 this index of solar activity is represented at the daily scale (Figure 2, bottom). The Group Sunspot Number [*Hoyt and Schatten*, 1998] is recommended to be used in favor of the traditional Wolf numbers, when analyzing the historical solar variability based on sunspot numbers [*Usoskin and Kovaltsov*, 2004; *Vaquero*, 2007]. Here we have plotted both indices to highlight their differences, particularly around the 11-year solar cycle maxima. Nevertheless, independently of the index adopted, according to Figure 2, the event of October 1870 occurred well within the maxima period.

[7] The main objective of this work is to present a comprehensive set of descriptions and records of the intense aurora that occurred on 24–25 October 1870, registered at several places (Figure 3). These records include observations of auroras but also records of disturbances in the geomagnetic field observed in different stations, such as Lisbon and Coimbra (Portugal), Greenwich (United Kingdom), Munich (Germany), and Helsinki (Finland). Some places of interest where the aurora was observed or the geomagnetic field was measured during the 1870 space weather event are listed in Table 1, including their geographical coordinates and geomagnetic latitude (at the time of the storm) computed using the *gufm1* geomagnetic model [*Jackson et al.*, 2000; *Jonkers et al.*, 2003]. Finally, we present some considerations on the most likely solar source region of this event.

2. Eyewitness Reports of the Aurora

[8] The 24–25 October 1870 aurora borealis was widely observed from Europe and the northeastern United States; however, scattered observations were also performed in the Middle East, southern United States, and three reports from the Southern Hemisphere. The unusual amount of auroral observations at relatively low latitudes in Europe and the United States triggered a large number of descriptions in several newspapers. In the United States, the 25 October 1870 edition of the *New York Times* reported sightings on 24 October in Cleveland and Cincinnati at 0500 LT [*New York Times*, 1870a]. On 27 October, the same newspaper reported that "we have been visited with an auroral display of an unusual and beautiful character. The exhibition, which has been widely observed throughout the country, has continued for several nights, but was most brilliant in this vicinity on Monday [day 24] night and Tuesday [day 25] morning" [*New York Times*, 1870b, p. 4]. That edition of the *New York Times* also highlights that "the peculiarity of all these displays, like that of New York, consisted on the bright crimson hue of the spurs or brushes of light" [*New York Times*, 1870b, p. 4]. A very curious remark in this article was that "modern science has suggested, without conclusively proving, various causes for the aurora, but the frequent and harmless recurrences of the displays, their common characteristics, and the explanation of other mysterious natural phenomena prevent the 'northern lights' from

Table 2. Low-Latitude Auroras During the Period 1859–1958[a]

Date	Low-Latitude Extent (deg)	Reference
2 Sep 1859	20	*Kimball* [1960]
24–25 Oct 1870	23	This work
4 Feb 1872	19	*Silverman* [2008b]
25 Sep 1909	30	*Silverman* [1995]
14 May 1921	30	*Silverman and Cliver* [2001]
25 Jan 1938	30	*Cliver and Svalgaard* [2004]
11 Feb 1958	28	*Adem* [1958]

[a]Modified from *Cliver and Svalgaard* [2004, Table VII].

longer exciting fear'' [*New York Times*, 1870b, p. 4]. As noted above, the potential for ''harm'' in our modern technology-based society has grown significantly in the intervening years.

[9] In a letter to the editor of the *London Times* published on 31 October 1870, E. J. Loewe from the Highfield-House Observatory, near Nottingham, writes that ''the brilliancy and redness on the 24th inst. [October] were so remarkable that it is 22 years since any approach to this grandeur has been seen. . .'' [*Loewe*, 1870, p. 6]. This letter also observes that ''although not so brilliant on the 25th inst., the phenomenon was even more singular'' [*Loewe*, 1870, p. 6]. The letter proceeds to give a detailed description of the aurora configurations. The effects of this event on disrupting telegraphic communications are described in a letter by R. S. Culley published also in the 31 October 1870 edition of the *London Times* [*Culley*, 1870]. This issue also contains a letter by T. H. Morgan detailing the 24 October aurora as seen on Stresa, Lago Maggiore, northern Italy. The writer emphasizes that ''we had here last evening the most magnificent Aurora Borealis it has ever been my lot to witness'' [*Morgan*, 1870, p. 6] and that ''no one here remembers so brilliant a phenomenon of such extensive dimensions, a remarkable one in 1848 having been only one-third as extensive'' [*Morgan*, 1870, p. 6].

[10] Many small notices appeared in Spanish newspapers with brief accounts and descriptions of the aurora. However, these notices are not very useful, because the descriptions are brief and without details (Table 3). Nevertheless a systematic search in newspapers would probably increase the number of reports.

[11] Descriptions of the aurora have also been published in several major popular science books. *Flammarion* [1873] signals the 24 October aurora observed by him in Paris as a notable and magnificent phenomenon. In his description, *Flammarion* [1873] notes that, during the most intense phase of the aurora, a tapestry of luminous red lights with greenish golden undulations could be seen 50° above the horizon, filling one third of the sky. A little later in the center of the aurora, a deep focus of light sent a ray toward the zenith, with the white light being disseminated at the borders like silver dew. This was followed by the appearance of a red ray on the left-hand side of the sky that almost reached the zenith. The sky remained illuminated as if huge sparkling firework sticks were being burned until the end of the phenomenon. According to this author, the 25 October aurora was less intense and shorter in time than the one on the previous day, and the sky remained clouded during the aurora. The famous French scientist A. Guillemin also provides a brief description of the event in a book dedicated to various electric and optic meteors [*Guillemin*, 1887]. This auroral display was also described by *Newton* [1955] in his popular science book *The Face of the Sun*, where he describes the account by Thomas Paulin on 24 October from Winchmore Hill, near London. It should be stressed that *Newton* [1955] only includes in his compilation the most outstanding auroral displays, namely Halley's description of the 16 March 1716 event and also Captain James Cook's famous sighting of the 17 February 1773 aurora.

[12] Taking into account the intensity of this unusual display it would be expected that more serious scientific journals would report with more detail different characteristics of this event. The British journal *Astronomical Register* [*Editorial Board*, 1870a, p. 268] emphasizes the ''extraordinary beauty and unusual intensity of the auroral displays of October.'' It also indicates several sightings in England, Scotland, France, Italy, and Greece, with an ''intense red color being noticed in all these places'' [*Editorial Board*, 1870a, p. 268]. The same journal also states that ''in England, one of the most noticeable features was the dome-like appearance of the streamers—as distinctly marked as the longitude lines on a globe'' [*Editorial Board*, 1870a, p. 269]. *Astronomical Register* publishes the description of the auroras seen at the

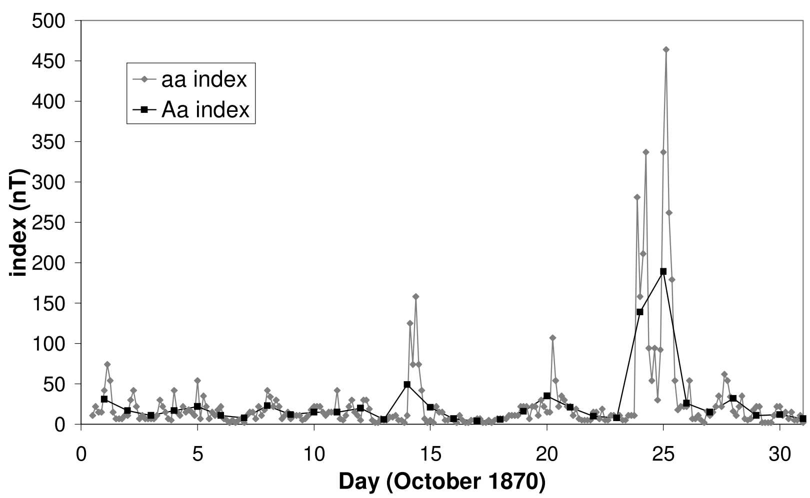

Figure 1. The *aa* and *Aa* indices during October 1870.

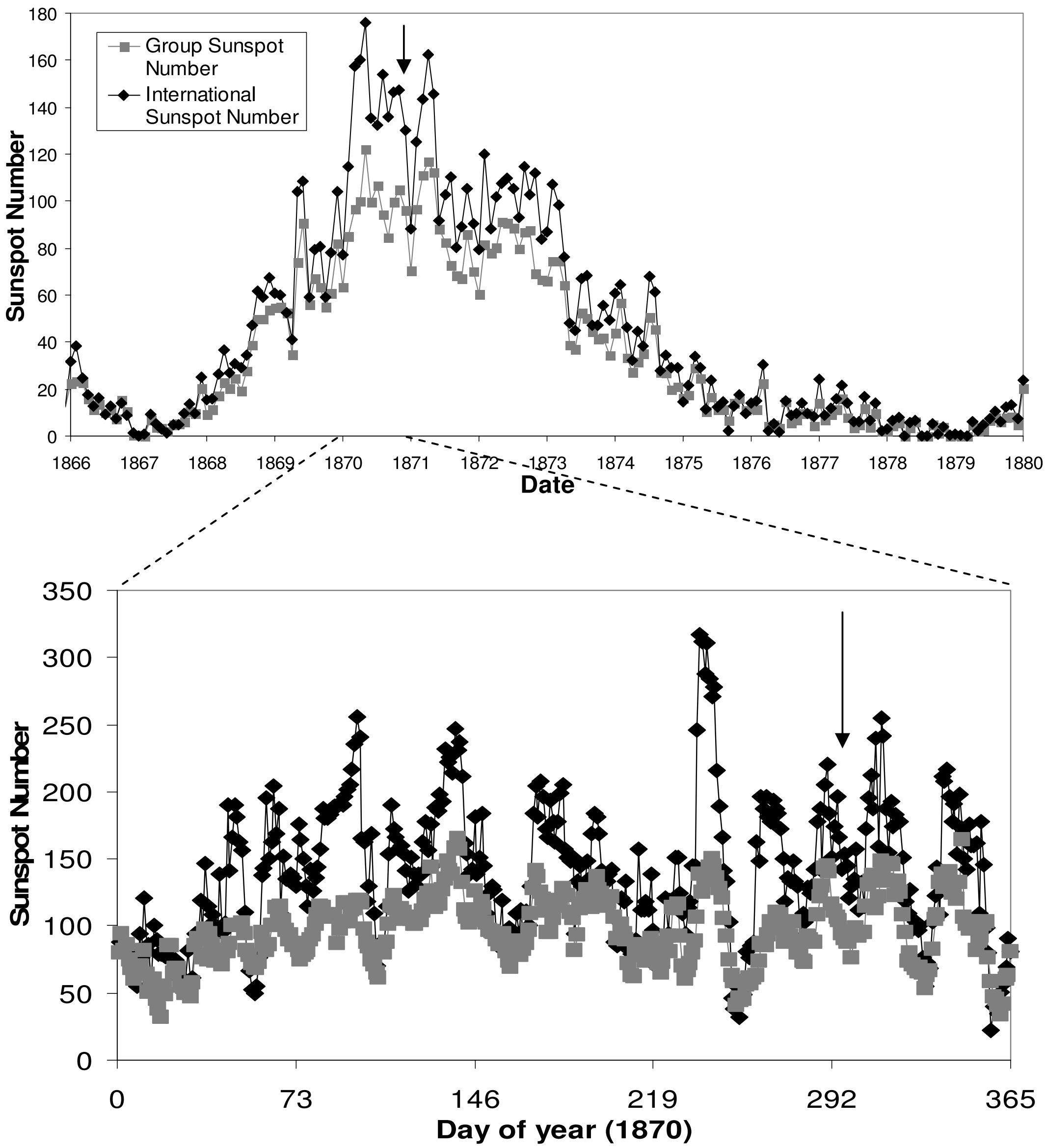

Figure 2. Sunspot numbers around the 1870 space weather event in monthly (top) and daily (bottom) resolution.

Observatory of Mr. E. Crossley, in Halifax (Scotland) on the 24 and 25 October, where the phenomenon "attracted the attention of all and excited the fears of many [on the 24]" [*Gledhill*, 1870, p. 270] and mentions "splendid Aurora Borealis" sightings in Hull (England) on the same days [*Editorial Board*, 1870b, p. 270].

[13] The French publication *Comptes Rendus* has extensive descriptions of the 24 and 25 October phenomena observed in Paris by *Chapelas* [1870], *Salicis* [1870], and *Guillemin* [1870] and as observed in Vendôme by *Renou* [1871]. In Italy, *Donati* [1870] describes in *Astronomical Register* the 24 October phenomenon as "a most splendid" aurora observed in Florence (Arcetri Observatory). The Florence Observatory received news that the aurora had also been observed at Lyons, Turin, Milan, Genoa, Leghorn, Naples, Otranto, Catania, and other places.

[14] The use of spectral analysis to characterize the light of the aurora was rare in those days; in fact, such procedure had only just been started by Anders Angström in 1867 [*Bone*, 2007]. Therefore we were fortunate to discover an auroral spectrum obtained by *Zöllner* [1870] from Leipzig during the night of 25 October (Figure 4) using a miniature spectroscope (type Browning). The most outstanding characteristic of this spectrum is the green atomic oxygen (557.7 nm) emission, present in all sky zones. In some zones of the sky, red lines were also visible (probably, red emissions at 630.0 and 636.4 nm wavelengths).

[15] The *Annals of the Astronomical Observatory of Harvard College* [*Bond et al.*, 1889] also provide a brief description of the 24 October 1870 aurora in their compilation volume of meteorological observations between 1840 and 1888.

[16] The Royal Greenwich Observatory classified the great geomagnetic storms recorded at the observatory between

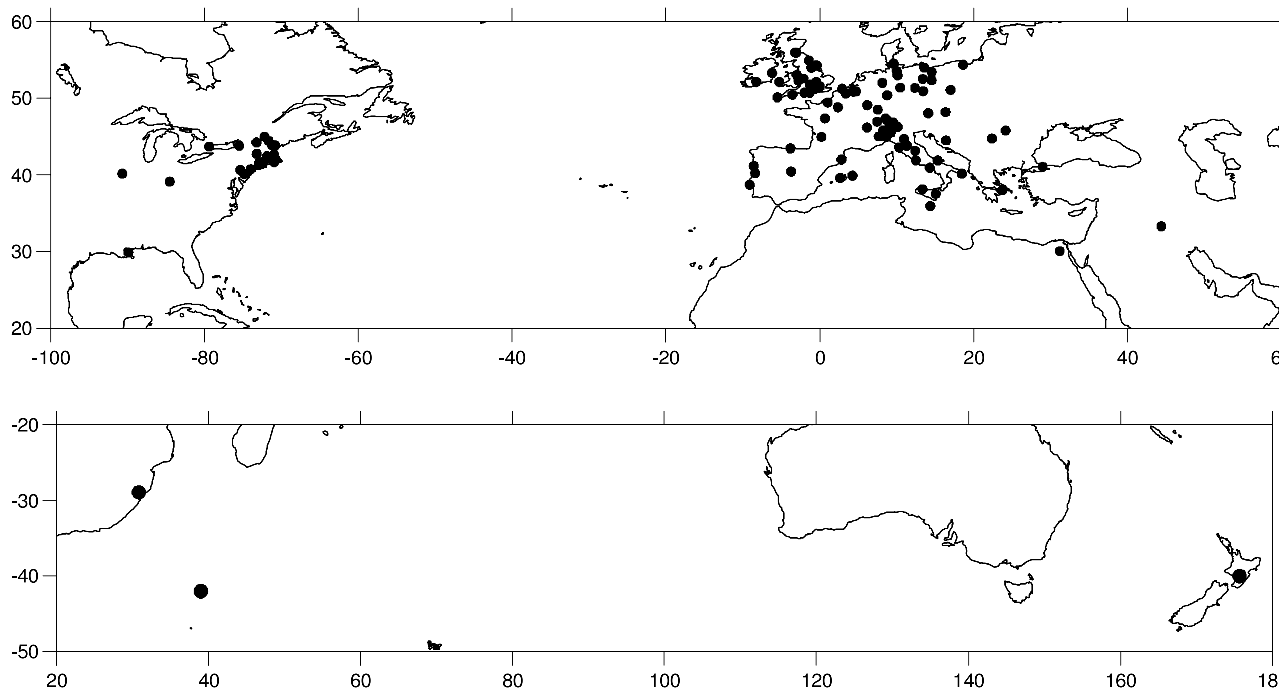

Figure 3. Geographic locations of northern (top) and southern (bottom) hemispheric records obtained from all the sources used in this work for 24 October 1870.

1840 and 1874 and lists the 24 and 25 October 1870 storm as number 44 [*Jones*, 1955]. However, it should be noticed that according to this reference, one of the peculiar characteristics of this episode corresponds to a double storm. On a note to the storm, it is written that "this great storm appears to fall into two parts, the maximum phase of each being associated with brilliant auroral displays recorded from the southern parts of Great Britain. The aurora was recorded at Cairo and eastwards to Baghdad. Moreover, a brilliant display of the Aurora Australis was recorded from Natal (lat. 28½°S)… On Oct. 24 at about 20h and on Oct 25 at 18h, the auroral displays culminated in the formation of a corona, seen from England a few degrees south-east of the zenith… On the previous evening at 18h, when a corona was also reported just south of the zenith, the same pattern of trace movements occurred but not to so marked and extent. The two auroras were also characterised by their deep red colour. At the time of this dual storm the central region of the Sun's disk was spotted, but no spot was large" [*Jones*, 1955, p. 106]. We should note that all times (unless otherwise noted) are expressed as local times.

[17] *Silverman* [2008a] collected 120 different observation locations for this event, with 90 being relative to the 24 October aurora and 70 to the 25 October event. From this comprehensive data set of auroral global observations we have chosen those relative to the 24 and 25 October 1870 event and have plotted (for 24 October only) the locations on Figure 3, including also our records. This figure provides a global overview of the event. We can confirm that the aurora was observed in Cairo (geomagnetic latitude 23.4°N) on both occasions (24 and 25 October). *Silverman* [2008a] also has a set of short descriptions of the event observed in New England in the states of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont. These descriptions were extracted from the larger set of auroral observations compiled by Silverman from various sources for the 1740 to 1948 period.

[18] Despite the large number of records mentioned above, most of these sightings lack careful descriptions, namely; hour, orientation, altitude, color, movements, etc. Nevertheless, despite the large number of auroral observations mentioned above we have located three comprehensive descriptions of this event that are presented in the following subsections.

2.1. Tours (France)

[19] The aurora observed at the Tours (France) meteorological observatory was thoroughly described by *Fron* [1870] in the *Bulletin International* (25–30 October 1870). On 24 October at 1730 LT, greenish lights occupied the horizon, northwest of Tours. The lower portion of these lights progressively took the form of a well-marked luminous arc, with an approximate extension of 25° in width and 15° in height. Below the arc, hazy lights appeared over the dark sky, while above the arc the whitish color started to disappear, fusing itself progressively with the sky's color. This configuration resembled more and more a halo's arc. The aspect and position of this arc suggested that an aurora

Table 3. Some Examples of Notices That Appeared in Spanish Newspapers Containing Brief Accounts and Descriptions of the 24–25 October 1870 Aurora Borealis

Newspaper	City	Date	Pages
El Juez de Paz	Palma de Mallorca	25 Oct 1870	6
La Crónica de Menorca	Mahón	26 Oct 1870	3–4
El Menorquín	Mahón	26 Oct 1870	2–3
El Juez de Paz	Palma de Mallorca	27 Oct 1870	7
El Vigilante	Gerona	27 Oct 1870	3

Figure 4. Spectrum of auroral light during the night of 25 October 1870 by *Zöllner* [1870].

borealis was about to start. Fron identified two distinct phases of the aurora on 24 October. The first lasted from 1800 until 1930 LT, and the second began at 1950 and ended at 2030 LT. Of the two, the second period presented the most remarkable visual configurations of this aurora.

2.1.1. First Phase

[20] Between 1800 and 1815 LT, a few red blooded rays started to be visible in the east and west directions. At the same time, two isolated masses of red blood colored light appeared in the east and west directions, with a height of 15° above the horizon. Their color became more distinct with time, until 1900 LT, when the two regions were significantly prominent. At around 1930 LT, these two red regions decreased in intensity, leaving only visible the greenish luminous arch, which continued to reside in the same position as in the beginning of the aurora, with its center in the direction of the magnetic meridian.

2.1.2. Second Phase

[21] At 1950 LT the two red blooded regions reappeared in the east and west directions. In the east direction, the color was magnificent, and soon red rays started to develop and to elevate themselves with pulsating movements toward the zenith. Three of these rays were very distinct and bright. In between the two most eastern rays, a dark space resembled a set of very dark rays, as clearly defined as the red ones. The three red rays also showed a marked translation movement from east to west. Meanwhile, another ray, as bright as the east-direction rays, elevated itself upward at the west direction. Both east and west sets of rays passed over the observer's head at this time. Simultaneously, the auroral arc, with a very bright whitish green color, was visible above a dark region (see Figure 5). Divergent red rays appeared then successively between the east and west sets of rays, being visible immediately above the whitish arc and seaming to diverge from a point just above the horizon. These rays were greenish at its lower part and red in the upper zone. For brief moments the greenish light rose very high upward, but was replaced afterward by the dominant red color rising up to the zenith. At this moment the phenomenon showed its maximum splendor. During this period the auroral arc was always clearly visible. From this arc departed a large number of rays, forming sometimes a corona. Some of these rays even traveled upward toward the south, to rejoin the horizon in the direction of the magnetic needle prolonging, forming for brief moments a dome over the head. A white ray appeared in this moment almost in the north direction. Some dark rays were also visible during the corona phase. At the same time, a few small cumulus clouds, of a bluish color, were visible over the aurora's red rays, presenting an impressive contrast with the dominant color. At 2012 LT the auroral arc started to dim, the red rays quickly lost their brightness, and three sectors appeared in their position, one in the east, a second in the NNE, and a third in the west. Their color also dimmed progressively,

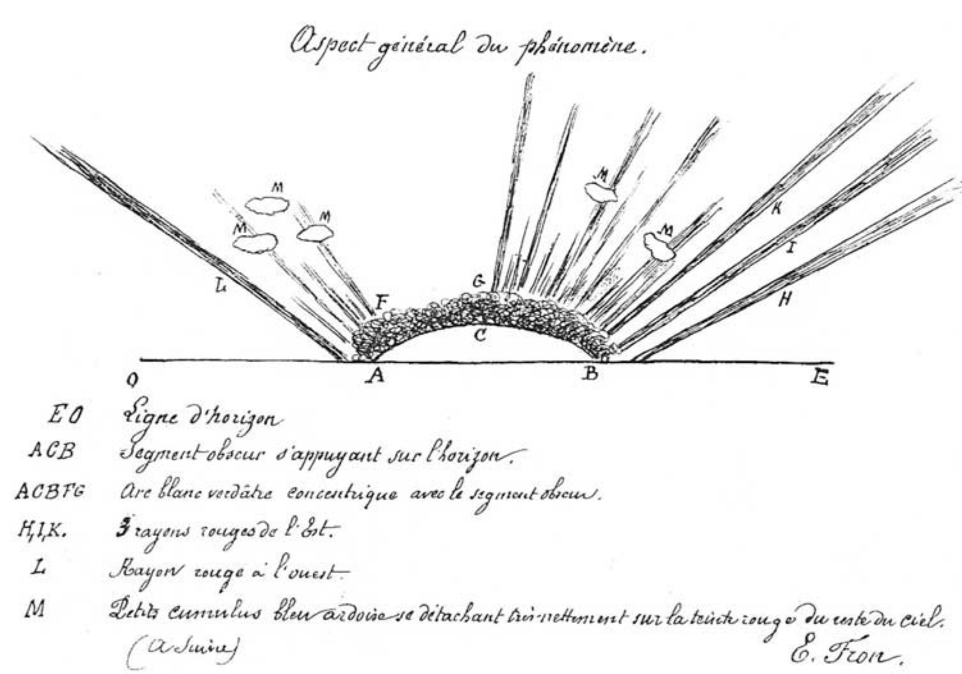

Figure 5. Sketch of the auroral display on 24 October 1870 by *Fron* [1870].

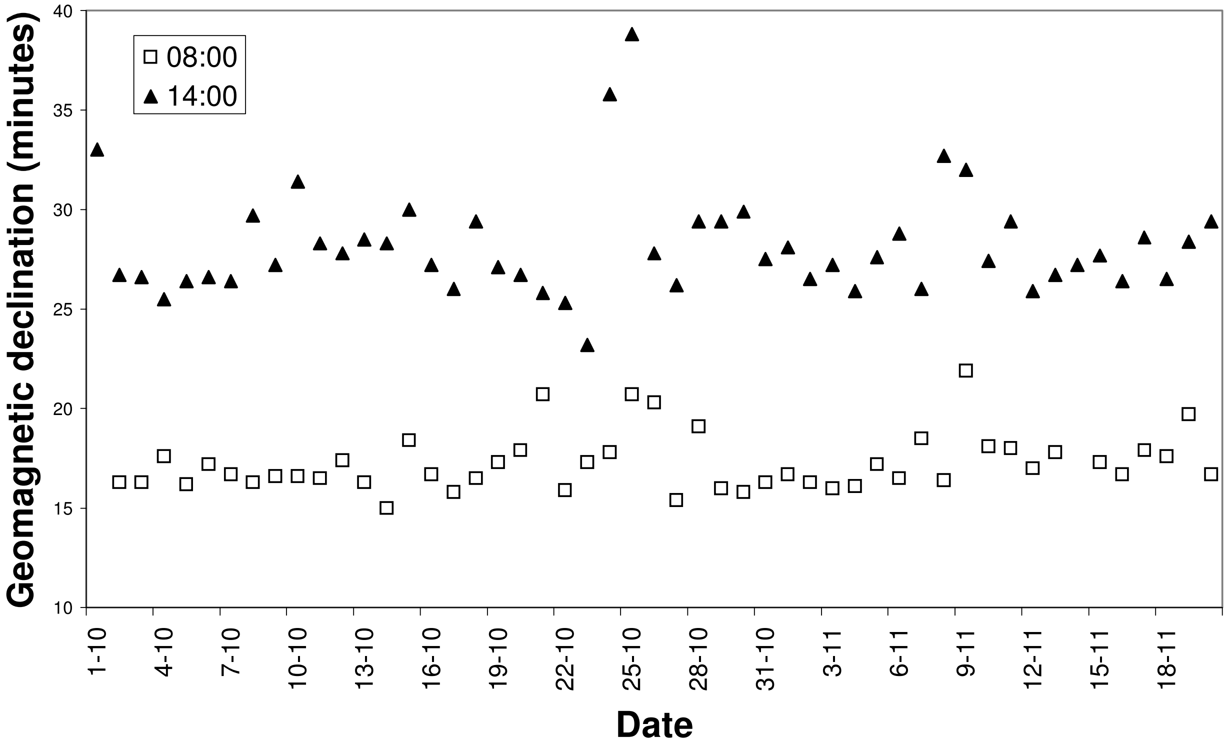

Figure 6. Geomagnetic declination (D) (W declination) in Lisbon at 0800 and 1400 LT for the period 1 October–21 November 1870. Absolute values are obtained by adding 20° to the minute values shown.

being soon replaced by a greenish mass of lights with a white center. At 2020 LT a ray rose and stopped at the west. Simultaneously another ray reappeared very quickly in the east, disappearing immediately after that, being replaced by a very beautiful greenish auroral band. Another ray detained itself in the east at about 2025 LT, starting from the planet Jupiter and leaving the Pleiades at its right side. This ray subsisted for a long time, until another ray started to rise at the west, being these the last observed rays during the aurora. Three auroral bands were next visible in the east, north, and west directions. They had all disappeared a little while after in this order. At 2100 LT there was no trace of the aurora borealis.

[22] *Fron* [1870] wrote that, on 25 October, similar visual phenomena occurred with similarities to those seen on the previous day, but with a somewhat different character. At 1730 LT the dark region seen in the northwest direction on the day before formed instead a transparent segment. At the same time, one or two whitish colored rays could be seen with the same configuration as the red ones on 24 October. He considered particularly remarkable the visualization of a series of red rose tinted clouds straight ahead (zenith) and toward the south direction. Some of these clouds moved at a considerable speed from southwest to northeast. At around 1930 LT the bright segment (arc) still subsisted, and at the same time, above the head two whitish colored bands could be seen. These bands disappeared at 2000 LT, when light rain had started to fall. The white bands reappeared though immediately after 2000 LT, first at the zenith and, shortly after, near the west and east directions. Around midnight, one very marked auroral band still existed in the west direction. At this moment (midnight) the observer positioned himself at the lower margins of the river Loire, in order to avoid the gas lights, and he could still clearly distinguish a whitish colored ray starting from NNE elevated by about 10° toward the zenith. Fron finally notes on his description that magnetic perturbations and telegraphic communications disturbances were signaled during the many aurora borealis sightings reported throughout western Europe.

2.2. Santander (Spain)

[23] The Spanish physicist *Fuertes Acevedo* [1876] observed the aurora from Santander, northern Spain. According to this report, the aurora begun on 24 October at 1945 LT and finished at 2014 LT, completely occupying the north quadrant, a large portion of the west quadrant, and a smaller part of the east quadrant. The color of the aurora was a brilliant uniform red. The observer indicates that it looked like the reflection of an immense fire. During the observation the sky was very cloudy, and dark spots due to the cloudiness were appreciated on the aurora. On 25 October, the sky was completely clear. At 1740 LT (20 min after the sunset) the observer saw brilliant skylights toward the north of a reddish violet color. When the twilight finished (the Sun reached −8° below the horizon at 1800 LT), the sky began to assume a strong red color spreading rapidly with an extremely intense tone toward the zenith and toward the south, persisting the area of the aurora in the north. Divergent rays began to appear forming a bow of reddish violet color at 1810 LT, and this configuration lasted for 5 min. Then the rays began to bend, vanishing almost instantaneously. Afterward, the intensity of the red brilliancy increased close to the Pleiades sector. A few minutes later, the red rays appeared again (but now with a more subdued

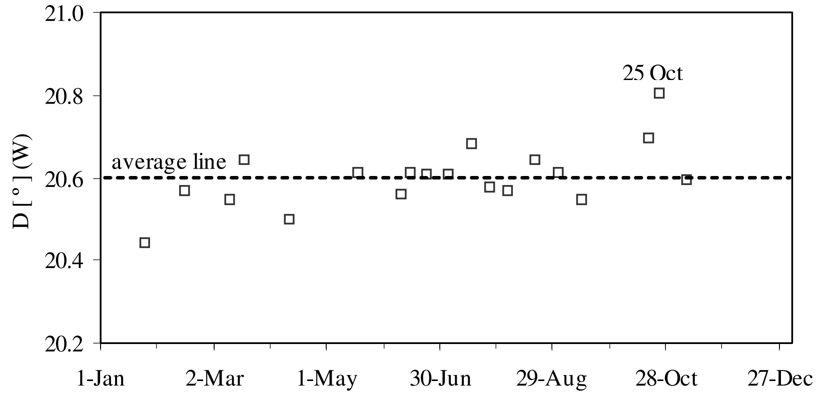

Figure 7. Absolute D (W declination) values in Coimbra during 1870. The anomalous value measured on 25 October (at 1500 LT) during the storminess period is labeled.

color) forming large bows that, rising on the horizon, were converging toward a point of the sky near the zenith. With the exception of the southern quadrant, the whole sky was surrounded by the most brilliant red light. The color (more intense toward the northwest) was spreading up to the Pegasus constellation. It remained with this configuration until 1935 LT (though with alterations in the color intensity), disappearing a little later.

2.3. Lisbon (Portugal)

[24] The annals (annual observation log books) of the Lisbon Geophysical Institute Infante D. Luiz recorded an aurora borealis on 24 and 25 October 1870. The description recorded is as follows:

[25] On 24 October the sky was cloudy during the day, but the weather was fair at nighttime. The aurora borealis lasted from 1853 LT, when the first bright lights began to be observed in the NNW direction, until after midnight. At 1900 LT the lights were less intense, decreasing significantly in intensity by 1910 LT. An arc started to be formed at 1915 LT in the NNE direction, with a full arc being visible up to WNW, between 10° and 40° in height. This arc was intersected by several rays extending up to 50° in height. The aurora's maximum intensity was observed at 1930 LT with a significant decrease occurring at 1940 LT. The phenomenon's intensity increased again at 1945 LT, with bright lights being visible in three regions in the NE, NNW and W 1/4 SW directions. The aurora's intensity decreased again at 1950 LT, with the bright lights being almost extinct by 2000 LT. From 2100 LT until after midnight, occasional bright lights were detected. The 24 October Lisbon records also mention, as it will be later shown, that large geomagnetic disturbances were identified in the magnetic instruments at 0900, 1500, and 1900 LT.

[26] On 25 October the weather was described as being very good. The aurora borealis started at 1745 LT and lasted until 2200 LT. The first bright lights appeared in the NNE direction, up to 60° in height. At 1807 LT a strip with about 80° in elevation passed over Beta of Ursa Minor. Lateral displacement of another strip, stretching up to 10°, toward the west direction was observed at 1810 LT. This strip continued to move toward the west at 1813 LT and greenish bright lights were visible at N1/4NE. At 1818 LT several strips were moving laterally. A dark zone appeared near the horizon at 1835 LT in the north direction, while above, a region of white greenish light could be seen at NE and WNW. Two red regions were also observed, with an initial height of 80° and after from 60° to 70°. At around 1900 LT a region of very bright white light was moving toward the west direction, until 1925 LT, disappearing at WNW. From 1910 until 1925 LT, red strips accompanied the bright light region. Very weak lights were then observed at northeast and WNW by 1925 LT. Occasional intense lights persisted until after 2200 LT. It is also recorded that on 25 October at 1500 LT large geomagnetic disturbances were detected, with an increase in declination and a decrease in the horizontal force.

[27] All the detailed descriptions of auroras indicate unusual features from low-latitude sites. Low-latitude sights of auroras are generally red and diffuse resulting primarily from an enhancement of the 630.0 nm [OI] emission due to the bombardment by soft electrons (<100 eV). The typical altitude for a low-latitude aurora is 250–400 km [*Silverman*, 1998].

3. Lisbon Geomagnetic Record

[28] Geomagnetic observations started at the Lisbon Geophysical Institute (38°42′59″N, 9°8′57″W) in 1857. Installed on a specially built magnetic house, away from other buildings, the first set of geomagnetic absolute instruments was constituted by a Jones Unifilar, to measure the absolute values of horizontal intensity (H) and the angular value of declination (D), and a Barrow's Inclinometer for the absolute measurement of inclination (I). In 1864 a Gibson's Unifilar was acquired to substitute the Jones Unifilar in the absolute measurements of H and D. The methodology used in the measurement process followed Lamont, and the equations

Figure 8. Magnetograms of H, D, and Z components, recorded in the Magnetic Observatory of Coimbra, showing the magnetic storms that occurred on 24 and 25 October 1870 related to the reported aurora borealis. The curves shown were reproduced and resized from the original ones, which were obtained with Adie variographs (normal running speed of 15.2 mm/h). Abbreviations are as follows: *ssc*, storm sudden commencement; *si*, sudden impulse; ?, missing and/or doubtful record.

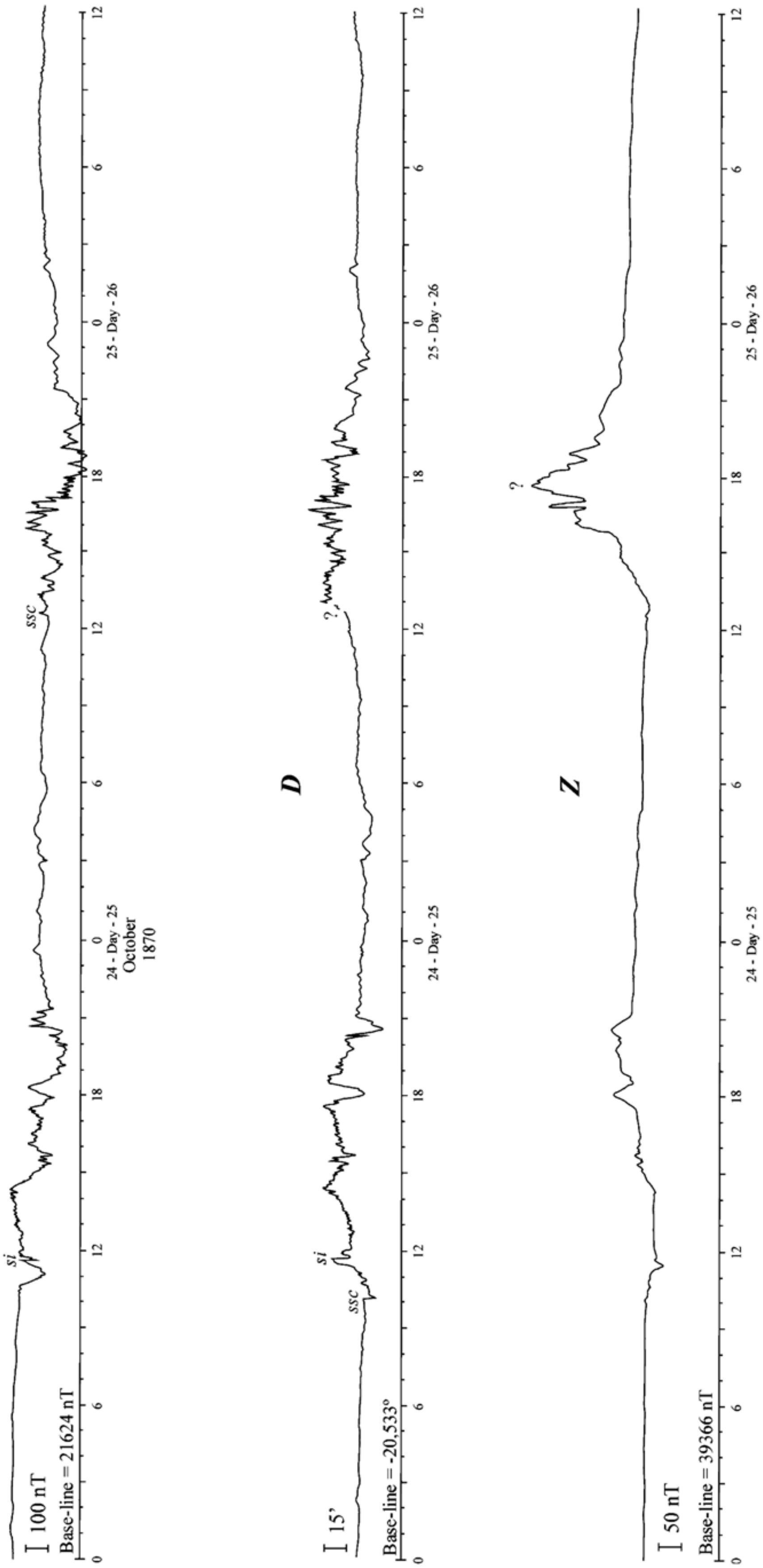
H
D
Z
100 nT
Base-line = 21624 nT
15'
Base-line = -20,533°
50 nT
Base-line = 39366 nT
si
ssc
?
24 - Day - 25
October
1870
25 - Day - 26
0
6
12
18

Figure 8

Table 4. Properties of Geomagnetic Storms Recorded in Coimbra on 24 and 25 October 1870[a]

	Time (h:min)		SSC		Max. Activity			Amplitude[b]		
Day	Begin	End[c]	Type	Amplitude[b] (D, H, Z)	Day	3hi	K	D	H	Z
24	10:10	22:00	SSC	8, –, –	24	7	7	37	182	48
25	12:40	24:00	SSC	–, 46, –	25	6	8	33	281	192

[a]Abbreviations are as follows: SSC, storm sudden commencement; 3hi, 3-h interval; K, maximum *K* index (see text and Table 5).
[b]D is in minutes of arc; H and Z are in nT.
[c]Main phase time end.

and procedures were in line with those adopted at the Kew Observatory.

[29] Through a set of magnetographs assembled in London by Adie, under the inspection of the Kew Observatory, the Lisbon Geophysical Institute also recorded continuously the variations of D, H, and Z geomagnetic field components. A special ground floor room was prepared at the Geophysical Institute building to store the magnetographs apparatus (Unifilar, Bifilar, and Lloyd's balance, for D, H, and Z variations recordings, respectively), which also included registering cylinders (magnetograms were obtained on a photosensitive paper) and a clock. This large room was built with no iron, and the temperature and low-humidity conditions were kept as constant as possible. Unfortunately, from the full set of continuous records, only the daily values of declination (D) obtained at 0800 and 1400 LT were published in the Institute's annals and are the only surviving daily values of magnetic observations. The old collection of magnetograms was lost on a fire in 1978 that destroyed part of the building.

[30] In 1870, the absolute measurements of inclination (I) were carried three times per month, while the absolute measurements of declination (D) and horizontal component (H) were carried twice and once a month, respectively. Additionally, the magnetographs were also observed through the incorporated telescopes and measuring scales three times per day at 1000, 1500, and 2100 LT. These values were then added to the baseline values (known through absolute measurements) and were confronted with the hourly variations obtained from the magnetograms. The 0800 and 1400 LT declination values published in the annals resulted from this process.

[31] The 24–25 October 1870 geomagnetic storm is detectable through the graphics of daily (0800 and 1400 LT) declination values in Lisbon, presented in Figure 6. On 24 and 25 October 1870, the 0800 LT declination values are 20° 17.8′W and 20° 20.8′W, respectively, slightly above the average (20° 17.3′W) for the period spanning between 1 October until 21 November suggesting the absence of significant disturbances around this time (Figure 6). However, the 1400 LT declination values show clearly a significant departure from the average value (20° 28.1′W), being 20° 35.8′W on 24 October and 20° 38.8′W on 25 October. The daily declination amplitude is thus 18′ on 24 October and 18.1′ on 25 October, much larger than the average daily amplitude (10.8′) for the considered period. It is clear that the 1400 LT measurements were obtained during the occurrence of the main geomagnetic disturbances on each day, as shown in the much more detailed Coimbra geomagnetic record, presented in section 4.

4. Coimbra Geomagnetic Record

[32] Solar Cycle 11 was about to begin when magnetic measurements started to be performed at the Magnetic Observatory of Coimbra (40°12′25″N, 8°25′24″W). The first absolute measurements of inclination (I) and horizontal intensity (H) were taken in June 1866. One year later, these measurements were complemented with the absolute values of declination (D) and with the continuous recordings of H, D, and Z. In 1870, the Coimbra Observatory was equipped with the same instrumentation as the one described for Lisbon: the absolute measurements were carried out on a Barrow's Inclinometer (I measuring) and Gibson's Unifilar (H and D measuring), while the continuous recordings of magnetic elements (magnetograms on photosensitive paper) were obtained with a set of Adie variographs (Kew model).

[33] In 1870 the absolute measurements of H and I were taken three times (on average) per month, while D was measured only two times a month. Among these series, only

Table 5. Geomagnetic *K* Indices Calculated for Coimbra Between 23 and 26 October 1870[a]

	3-h Interval							
Day	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
				K_H				
23					3	2	2	2
24	3	2	2	6	6	6	7	5
25	4	5	3	3	6	8	6	5
26	4	2	2	2				
				K_D				
23					3	2	1	2
24	3	2	2	7	6	7	7	3
25	3	5	3	3	6	7	7	6
26	5	2	2	3				
				K_{HD}				
23					3	2	2	2
24	3	2	2	*7*	*6*	*7*	*7*	*5*
25	*4*	*5*	3	3	*6*	*8*	*7*	*6*
26	*5*	2	2	3				

[a]For a given 3-h interval, *K* index is the number of the class (0–9) that is related to the maximum fluctuations of the horizontal components when compared to a quiet day; the Coimbra's lower limit for *K* = 9 is 350 nT. K_{HD} is the maximum index of K_H and K_D; cells with $K \geq 4$ (active field threshold) are italicized.

Table 6. Equivalent Amplitude *ak* Indices Derived From *K* Indices Calculated for Coimbra Between 23 and 26 October 1870[a]

	3-h Interval							
Day	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
23					21	10	10	10
24	21	10	10	*196*	*112*	*196*	*196*	*67*
25	*38*	*67*	21	21	*112*	*336*	*196*	*112*
26	*67*	10	10	21				

[a]Indices are in nT. Cells with $K \geq 4$ (active field threshold) are italicized.

Table 7. Data on Sunspot and Geomagnetic-Storm Derived From Greenwich Observations Compiled by *Jones* [1955]

	Date of Storm	
	24 Oct 1870	25 Oct 1870
Time of onset (UT)	1024	1200
Interval from sunspot max. (years)	+0.2	+0.2
Range D (minutes of arc)	88	>59
Range H (nT)	400	1150
Notable Z range (nT)	450	775

Table 8. Equivalent Amplitude *ak* Indices for Greenwich Between 23 and 26 October 1870[a]

	3-h Interval							
Day	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
23					0	14	10	0
24	14	6	6	*160*	*280*	*160*	*480*	*96*
25	*54*	*96*	30	30	*480*	*860*	*280*	*280*
26	*54*	*96*	30	30				

[a]The *ak* (nT) derivation was done according to *van Saben* [1972], using a lower limit for $K = 9$ of 500 nT. Cells with $K \geq 4$ (active field threshold) are italicized.

the declination data provides information about the 24–25 October geomagnetic disturbance. Despite the significant oscillatory behavior that characterizes the 1870s absolute declination data, it is unquestionable that the declination value measured on 25 October (at 1500 LT) deviates clearly from the average line of data (Figure 7). We therefore can take this deviation value (12.1′) as a first estimate of the magnetic storm's magnitude that occurred on that day.

[34] Fortunately we have the continuous recordings for a better characterization of the geomagnetic stormy events. In Figure 8 we reproduce the daily magnetograms curves for H, D, and Z between 23 and 26 October 1870. With an original length of 36.5 cm, these daily magnetograms were recorded with a speed of about 1.5 cm/h (normal running) and used to be replaced at noon (or approximately). Table 4 reports the properties of rapid variations recorded in Coimbra on days 24 and 25 October 1870. We can clearly distinguish two magnetic storms. The first one begins on 24 October approximately at 1010 LT and prolongs its main activity for almost 12 h. This storm begins with a very distinct (A type) and clockwise sudden commencement (*ssc*) on the D component. This impulse was not accompanied by similar phenomena on the other components, where we are able to see only small increments in magnetic activity followed by bays (being the H-bay particularly remarkable; Figure 8). However, around 1140 LT occurs a new sudden impulse (*si*), now perfectly clear on components D (12.4′ of amplitude and clockwise or positive sense) and H (68 nT of amplitude and negative sense), but very doubtful on Z. The maximum 3-h interval activity appears a few hours later between 1800 and 2100 LT (the seventh interval), with amplitudes of 37′ in D and 175 nT and 48 nT in H and Z, respectively. However, if we consider other time periods (yet less than 3 h), we find that H shows its maximum variation between 1420 and 1540 LT (between the fifth and sixth intervals) with 182 nT.

[35] The second storm begins on 25 October, approximately at 1240 LT, when the previous storm was still in the recovery phase. As in the previous disturbance, the magnetic activity starts after a very remarkable *ssc*, which this time clearly appears on the H recording (with an amplitude of 46 nT and positive sense); this sudden impulse was also most certainly present on the D component but was not recorded in the magnetogram (probably due to an extremely rapid movement of the magnet and the attached moving mirror). The second magnetic disturbance maintains its main phase also for almost 12 h, reaching the 3-h interval maximum activity between 1500 and 1800 LT. Considering, as we have done for the first storm, other time periods, we find that D shows its maximum amplitude between 1620 and 1850 LT (between the sixth and seventh intervals) with 33′, while H attains its maximum amplitude between 1550 and 1820 LT with 281 nT.

[36] A major difference between the two consecutive geomagnetic storms is clearly put into evidence when we consider the behavior of the Z component. When compared with the horizontal components, the vertical one shows a larger maximum amplitude difference, with its maximum range during the second storm being 4 times higher than that recorded in the first one (Table 4). We presume, however, that this anomalous behavior might be related with the local effects of induced underground currents, which affect particularly the Z component [*Mayaud*, 1967].

[37] Using magnetograms of H and D components we have also computed the geomagnetic *K* indices (Table 5) for the period that spans between days 23 (after 1200 LT) and

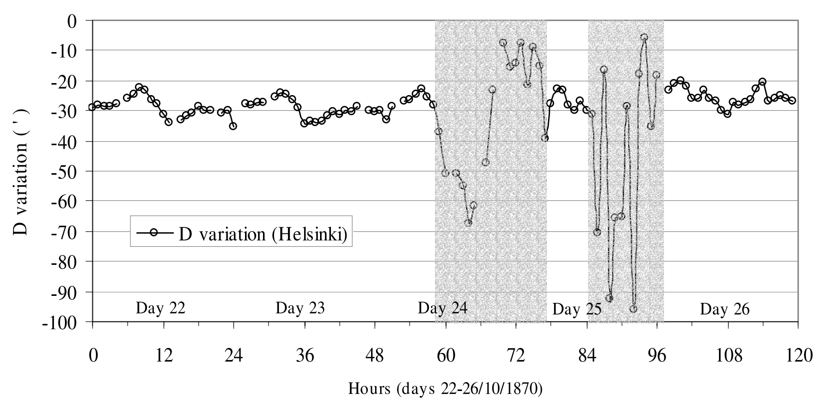

Figure 9. Relative hourly values of component D observed in Helsinki between 22 and 26 October 1870; the shaded areas cover the most perturbed periods.

Table 9. Geomagnetic *K* Indices From Helsinki Observatory Calculated (Using the FMI Method) From Hourly Values of *D* Between 23 and 26 October 1870[a]

	3-h Interval							
Day	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
23					3	3	2	–
24	3	–	0	3	–	6	–	–
25	6	8	4	4	8	9	9	8
26	–	2	4	2				

[a]Data courtesy of H. Nevanlinna.

Table 10. Hand-Scaled Geomagnetic *K* Indices From Royal Greenwich Observatory Between 23 and 26 October 1870[a]

	3-h Interval							
Day	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24
23					0	2	1	0
24	2	1	1	*6*	*7*	*6*	*8*	*5*
25	*4*	*5*	3	3	*8*	*9*	*7*	*7*
26	*4*	*5*	3	3				

[a]Data obtained from http://www.geomag.bgs.ac.uk/cgi-bin/k_indices. Cells with $K \geq 4$ (active field threshold) are italicized.

26 (until 1200 LT). From these *K* indices (which have been designed by Bartels in 1939 in order to monitor the transient irregular variations of the geomagnetic field) we derived (according to *van Saben* [1972]) the local equivalent amplitude *ak* indices (Table 6). Finally, the daily *Ak* indices of geomagnetic activity, derived as the average of the eight 3-h *ak*, were computed for the two stormy days. The obtained results (Ak_{day24} = 101 nT and Ak_{day25} = 113 nT) show a very high level for the disturbances recorded on 24 and 25 October 1870 in Coimbra, and lead us to classify this geomagnetic activity as severe geomagnetic storms.

5. Other Geomagnetic Records

[38] For a more complete account of the geomagnetic storm of 24–25 October 1870 we compare the Coimbra and Lisbon recordings with data from the well known geomagnetic observatories of Greenwich (51°28′38″N, 0°W), Helsinki (60°10′0″N, 24°57′0″E), and Munich (48°08′49″N, 11°36′29″E). Although not based on a comprehensive geographic covering, this comparison provides some insights on the storm behavior in the subauroral latitudes. According to *Jones* [1955], who has compiled sunspot and geomagnetic storm data derived from Greenwich observations, the great storm appears to fall into two subepisodes (Table 7). A simple comparison of the H-ranges obtained for these two subepisodes reveals that the second storm exhibits a magnitude about 3 times bigger than the first one. Such difference is not observed in the Coimbra recordings, where the second storm appears to be only slightly larger. Computing the average of daily *Ak* indices for both stormy days and both stations (Tables 6 and 8), we see that the geomagnetic activity observed on days 24 and 25 October 1870 in Greenwich ($Ak_{ave24/25}$ = 207 nT) was 2 times higher than the one observed in Coimbra ($Ak_{ave24/25}$ = 107 nT).

[39] The storm of 24–25 October 1870 was also recorded at the Helsinki [*Nevanlinna*, 2004] and Munich geomagnetic observatories. Table 9 presents the Helsinki *K* indices computed from hourly readings of D (the H hourly values show considerable gaps giving a less consistent *K* index calculation) and shows, when compared with *k* indices of Coimbra (Table 5) and Greenwich (Table 10), a higher geomagnetic activity. The relative hourly values of declination observed at Helsinki between 22 and 26 October 1870 are represented in Figure 9, which clearly shows the main perturbations on days 24 and 25 separated by a short period of relative quietness. The maximum needle swing occurred on day 25, between 2000 and 2300 LT, with a range of 90.5′. This maximum amplitude seems to be of the same order as the one observed in Greenwich (the Greenwich's amplitude data for this day is quite imprecise), but 3 times higher than that observed in Coimbra and Munich (bearing in mind that Munich's hourly data covers partially the stormy period) (Figure 10).

[40] We believe that the brilliant auroral displays of 24 and 25 October 1870 resulted from a combined storm with two well individualized main phases (preceded by two remarkable *ssc*), even though occurring close to each other, with less than 12-h separation (Figure 11). This apparent unusual temporal behavior of the geomagnetic disturbance

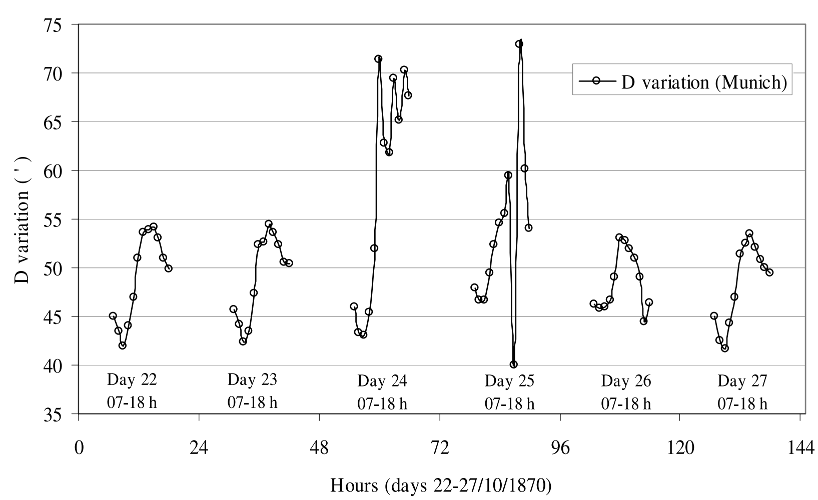

Figure 10. Relative hourly values (0700–1800 LT) of component D observed in Munich between 22 and 27 October 1870. Data courtesy of H. McCreadie, Geophysical Observatory, Fürstenfeldbruck.

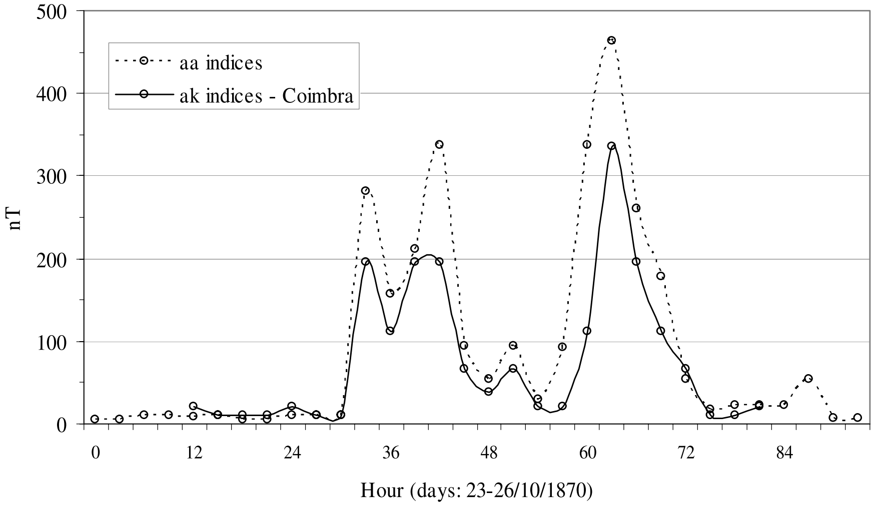

Figure 11. Planetary *aa* indices and local (Coimbra) *ak* indices for dual geomagnetic storm of 24–25 October 1870.

led us to look more in depth on the possible existence of similar events. For this purpose we have used the eight-point running average of the *ap* index (*Ap** index) relative to two sets of large geomagnetic disturbances. The first set is relative to the 10 storms with approximate amplitude, while the other set refers to the biggest 10 storms according to *Ap** rank. Without performing a comprehensive analysis (that is out of the scope of this paper), the obtained results show that the double storms appear to be unusual, since on the basis of the two studied storm sets (20 events) we have only found three cases (24 January 1949, 2 September 1958, and 28 October 2003) where the *Ap** curve shows a box-type shape due to the presence of a nearby double maximum (Figure 12).

6. The Sun in October 1870

[41] There is a great scarcity of data describing the state of the Sun during 1870. Unfortunately, we lack good quality sunspot area measurements for this epoch, because the Royal Greenwich Observatory began their systematic observational program only in 1874. Moreover, the available measurements made by de la Rue and coworkers in the 1860s finished in 1868 [*Vaquero et al.*, 2002, 2004]. Fortunately we have come across relevant information regarding the specific solar source of the 24–25 October storm. The amateur astronomer T. H. Buffham [*Buffham*, 1871] wrote a letter to the editor of the *Astronomical Register* saying, "Many persons observed a spot on the Sun through the fog on the 18th ult. [18 October 1870], but its telescopic appearance deserves notice. With 2.9-inch refractor, and power 74, at 1 $^{3}/_{4}$ h., it was found to consist mainly of two umbrae of unequal size, the larger having an unusually large black nucleus, quite round, surrounded with a narrow grey ring, which was close to the W. side of the umbra. There was also another black patch, of smaller dimensions, near the opposite side. The diameter of the large nucleus I estimated from subsequent measures of the umbra to be fully 20″. I have not seen any notice of a brighter ring surrounding the nucleus having been before observed, but the inference is obvious that its relation to the 'cloudy stratum' of Dawes is analogous to that of the brighter inner edge of the penumbra to that part. On the 20th

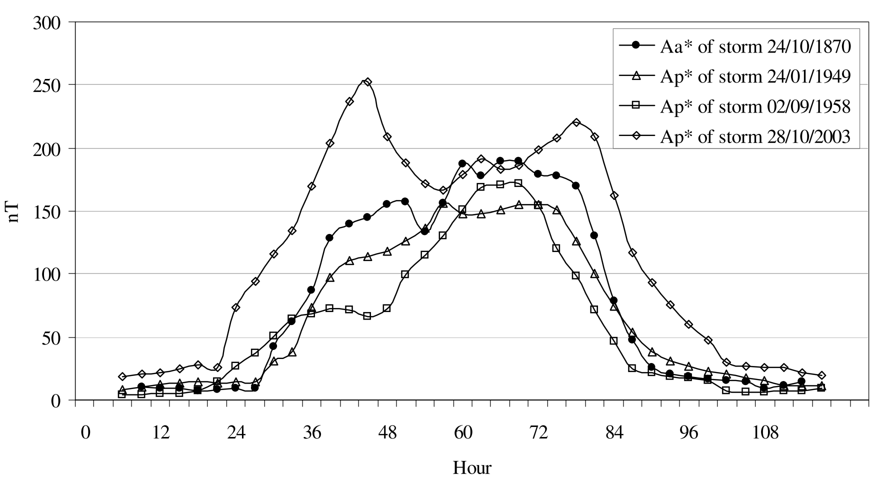

Figure 12. Planetary indices (*Aa** and *Ap**) for several geomagnetic storms with a twofold morphology.

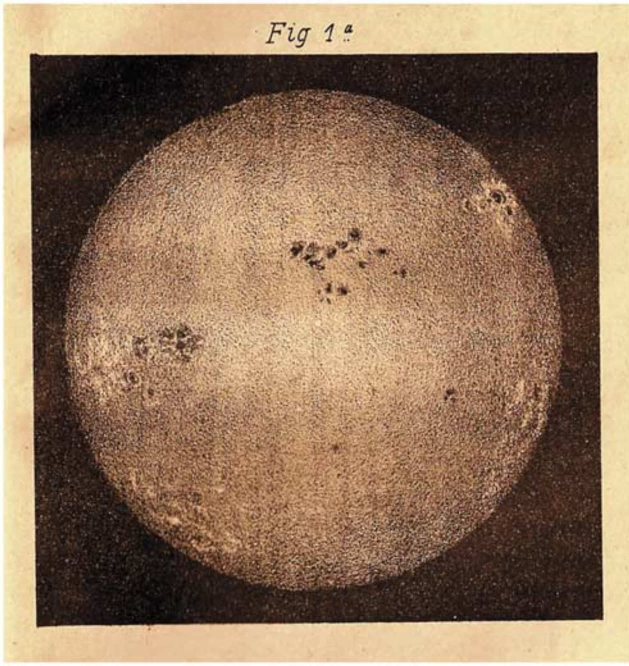

Figure 13. Photograph made by Rutherfurd in New York on 22 September 1870. It was published in the famous book *The Sun* [*Secchi*, 1879, Plate I].

at 10 h., I could find but traces of 3 or 4 darker specks on a very dark umbra of very similar form, while some small spots E. had tiny black points in their umbrae" [*Buffham*, 1871, pp. 18–19]. In the section "Miscellaneous Notices" of the same journal, we can read, "Sun Spot.—We are indebted to Mr. A. P. Holden for a beautiful photograph of some careful drawings made by him of a great sun spot observed at 8.0 A.M. on September 23, 24, 28, and 29, with a three-inch refractor, powers 60 and 130" [*Editorial Board*, 1871, p. 23]. Thus, we know that a great sunspot (visible without the aid of a telescope) was present in the solar disk in the epoch of the storm and that this sunspot had been already observed during its previous solar rotation.

[42] We have additional information on this sunspot from the work of 19th century solar observers. In the famous book *Le Soleil* (*The Sun*) by *Secchi* [1879] there is a photograph made by Rutherfurd on 22 September 1870 (Figure 13). In this photograph, two large solar groups are perfectly visible. Both sunspot groups can be thought as good candidates to be considered the original solar sources of the great 1870 space weather event.

[43] We know, approximately, through the solar observations made by *Spörer* [1874], the location of solar groups existing during the great storm epoch. According to Spörer, the large group in Figure 13 (left area of photograph) corresponds to group 273 that crossed the solar central meridian during the day 24 September (solar rotation number 131). After the next solar rotation (132), this group was renumbered as group 299, crossing the solar central meridian on the day 21 October. Another great group (central area of photograph) visible in Figure 13 would disappear in the next solar rotation. Thus, we think that the more plausible solar source for the event was the number 299 group in the *Spörer* [1874] classification. It should be stressed that this great sunspot group was present in the Sun for a considerable length of time, namely during the Spörer solar rotations 127–132 (May–October 1870).

7. Conclusion

[44] The great solar storm that took place on 24–25 October 1870 has been identified before as being part of the small subset of extreme low-latitude auroras [*Silverman*, 2006] (see Table 2). However, to the best of our knowledge, this intense solar storm and its subsequent impacts in our planet have not been addressed in depth in previous studies. Nevertheless, it is widely accepted now that there is an obvious interest to study the largest solar storms that have occurred between the 1850s and the 1960s. These storms occurred before the use of satellite data, but after the implementation of many geomagnetic stations, with precise hour/daily measurements of the three components of the magnetic field.

[45] We have shown that the auroras that have occurred on both nights were widely observed in northwestern America, Europe, and sections of the Middle East (Figure 3). We have made an effort to compile all the available information that was registered at the time with particular emphasis to the best auroral descriptions but also to the early geomagnetic data from several stations in Europe.

[46] The spectacular aurora episodes associated with this storm were observed throughout southwest Europe by many people, from the lay man to the more knowledgeable. Here we have described in length the auroras characteristics observed at three stations located in France (Tours), Spain (Santander), and Lisbon (Portugal). Among many peculiarities, these observations confirm that the aurora was observed at low latitudes, as some observers in Iberia even describe the event with bands extending toward the south. Moreover, at these latitudes the aurora is generally red and diffuse resulting primarily from an enhancement of the 630.0 nm [OI] emission due to the bombardment by soft electrons (<100 eV). Our lengthy descriptions refer in detail to the appearance (on both 24 and 25 October) of reddish bands; however, they provide additional information on the appearance of several sectors characterized by greenish and bluish/violet rays. These colors show typical characteristics of auroras produced by very energetic electrons penetrating to lower atmospheric levels (approximately 90 km altitude) and exciting OI molecules but also molecular nitrogen. It should be stressed that the typical altitude for a low-latitude aurora is 250–400 km [*Silverman*, 1998]; however, very strong solar storm events (such as the one of October 1870) are known to induce auroras at even lower altitudes.

[47] Geomagnetic records (unavailable until recently) from two stations in western Iberia (Portugal) were particularly helpful to put in context the amplitude of the geomagnetic disturbances associated with this storm. Daily values in Lisbon, obtained in the morning (8.00) and afternoon (14.00) help to constrain the most active periods of this 2-day event. However, the magnetograms available for Coimbra are much more precise to pinpoint the exact sequence of events at the subhourly temporal scale, and furthermore to provide an objective assessment on the

magnitude of the disturbance. In particular, these continuous registrations show that the event was the result of a combined storm with two well individualized main phases occurring close to each other, with less than 12-h separation. The geomagnetic data from other European observatories, namely Greenwich, Munich, and Helsinki confirm this double nature of the storm.

[48] We were fortunate to identify two large sunspot groups in a photograph made by Rutherfurd on 22 September 1870, published in the book *The Sun* by *Secchi* [1879]. Both sunspot groups could be considered as potential candidates to the original solar sources of the great storm of 1870. However, we were able to further select from these two hypotheses after analyzing data from *Spörer* [1874]. According to this author, the great sunspot group clearly observed in Figure 13 corresponds to group 273 (that crossed the solar central meridian on 24 September). Afterward this group was renumbered as group 299, crossing the solar central meridian on 21 October, i.e., 3 days before the solar storm strikes our planet. Therefore we believe that the most plausible solar source for the event was the group number 299 in the *Spörer* [1874] enumeration list.

[49] **Acknowledgments.** The authors are in debt to Heikki Nevanlinna and Heather McCreadie, who provided the Helsinki and Munich geomagnetic data, respectively. The assistance provided by Alexandra Pais and David Vaz with the Coimbra geomagnetic data is also gratefully acknowledged. The authors are in debt to Andrew Jackson for providing access to the geomagnetic database as well as to the *gufm1* model. We are also particularly thankful to Sam Silverman for providing his historical aurora data set from the National Space Science Data Center. J.M.V. acknowledges the Programme "José Castillejo" of the Spanish Science Ministry. The authors acknowledge the geomagnetic data and auroral descriptions provided through the Portuguese project Signatures of Environmental Change in the Observations of the Geophysical Institutes (SIGN) under POCTI/CTA/47803/2002.

[50] Zuyin Pu thanks Walter D. Gonzalez and another reviewer for their assistance in evaluating this manuscript.

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