Solar Physics (2006) 235: 419–432
DOI: 10.1007/s11207-006-0024-6

IDENTIFICATION OF POSSIBLE INTENSE HISTORICAL SOLAR STORMS DURING THE YEARS 1781–1788 INFERRED FROM AURORAE AND GEOMAGNETIC OBSERVATIONS IN RIO DE JANEIRO

JOSÉ M. VAQUERO
Departamento de Física, Escuela Politécnica, Universidad de Extremadura, Avda. de la Universidad s/n, 10071 Cáceres, Spain

and

RICARDO M. TRIGO
Centro de Geofísica da Universidade de Lisboa, Lisbon, Portugal; Departamento de Engenharias da Universidade Lusófona, Lisbon, Portugal
(e-mail: jvaquero@unex.es; rmtrigo@fc.ul.pt)

(Received 5 July 2005; accepted 2 February 2006)

Abstract. The reconstruction of solar activity during the late 18th century is a puzzle for researchers due to the scarcity of sunspot observations in that epoch. In this work, we analyse some details of the solar activity during the years 1781–1788, inferred from geomagnetic measurements and visual observations of aurorae performed by the Portuguese scientist Bento Sanches Dorta from Rio de Janeiro. We describe in greater detail four large solar storms that induced large changes in daily values of geomagnetic declination and, simultaneously, correspond to visual observations of aurorae described by Sanches Dorta.

1. Introduction

Historical observations of sunspots have provided contemporary researchers a privileged record of solar activity since the year 1610 (Hoyt and Schatten, 1998). Other procedures to reconstruct the solar activity during the last millennia have been used with great success, particularly those that employ cosmogenic isotopes (*e.g.* Solanki *et al.*, 2004). Nevertheless, records in documentary sources can provide a higher temporal resolution despite being limited to the last few centuries.

There are several sources available for obtaining information about the solar activity during the last centuries from documentary information. The usual procedure is to search for sunspot observations, although the shape of the solar corona during eclipses can also be used (Vaquero, 2003). Some authors have based their reconstruction only on old naked-eye observations of sunspots (Ogurtsov *et al.*, 2002; Vaquero, Gallego, and García, 2002). Another tool to obtain information on historical solar activity has been based on the use of old records of aurora observations

(Křivský, 1984; Silverman, 1992; Letfus, 2000). Better estimates on the frequency of historical aurora help to determine confidence intervals on long-term cycles and trends of solar activity, particularly for those periods with considerably less observations of sunspots (*e.g.* most of the 18th century). Interestingly, what used to be a highly controversial aspect on the fingerprint of solar activity in our planet's climate (Friis-Christensen and Lassen, 1991) has now become widely recognised (*e.g.* Benestad, 2003). While the exact physical mechanisms responsible for this association are not yet well understood, the fast growing evidence of significant climate phenomena driven by solar activity (Pap and Fox, 2004; Labitzke, 2005) further stresses the necessity to obtain the best reconstruction of solar variability over the last centuries.

It is now widely accepted that Hoyt and Schatten (1998) undertook the most comprehensive effort since 1610 to reconstruct solar activity by recovering a large quantity of historical observations of sunspots. Afterwards, some minor contributions with additional observations have been made (*e.g.* Vaquero, 2004; Vaquero, Trigo and Gallego, 2005), where the authors have shown that the number of days with records for the years 1784 and 1785 can be updated to 80 and 25 respectively. Nevertheless, the reconstruction realised by Hoyt and Schatten (1998) reveals some epochs that have very few observations, this is the case with the period that spans between 1777 and 1795 (Figure 1). The pronounced decrease in the number of available observations during those two decades corresponds to a significant drop

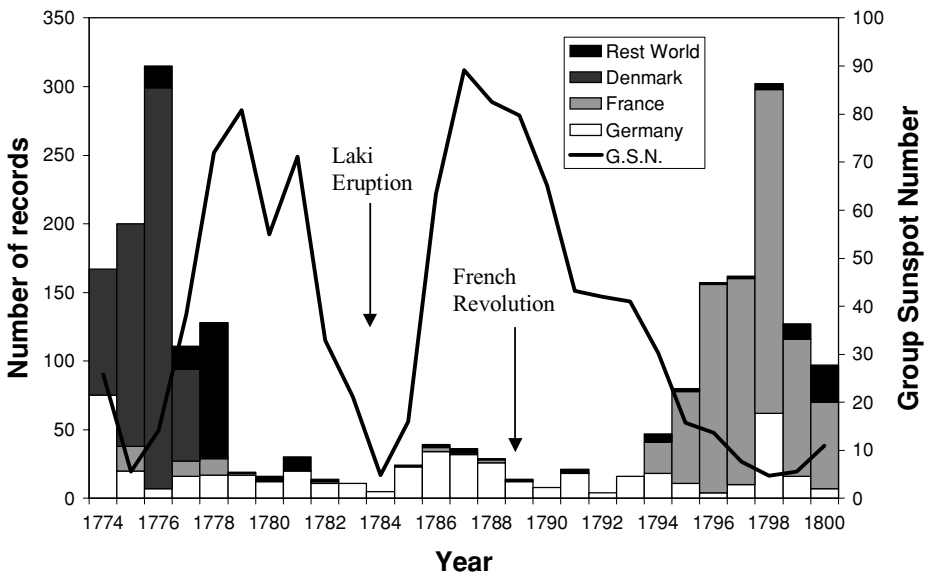

Figure 1. Number of days with records in the solar reconstruction of Hoyt and Schatten (1998) split by country and yearly values of Group Sunspot Numbers (*solid curve*). *Vertical arrows* correspond to the two major events that had a direct impact on the number of observations performed.

of interest of major astronomical observatories in solar activity monitoring (Hoyt and Schatten, 1997). Therefore, the number of people engaged in regular solar observations was extremely low. Moreover, according to Lalande (1771), the regular surveying of sunspots was placed at a very low order of priority on the observatories list of observations (14th of 18 duties). This dependence on a small number of observers can be appreciated if we split the number of observations for the last 25 years of the 18th century by country (Figure 1), where it is immediately striking that more than 90% of all sunspots observations were performed by observers located in just three countries, namely Denmark, France and Germany. Observers from the rest of the world (including England) were responsible for a small amount of observations. Germany kept a relatively constant number of observations throughout the period, obtained mostly by just one observer (Staudacher). On the contrary, during the early 1770s vast majority of observations were performed by two Danish observers (Horrebow and Liebog), while the 1790s was dominated by French observations, particularly by Flaugergues. This pattern highlights the enormous dependence of total sunspot observations on a handful of dedicated observers.

Finally, we have become aware of two additional factors for this significant decline in observations, namely the outstanding eruption of Laki, Iceland (1783–1784), and the French revolution (1789).

The unusually large eruption of Laki started in June 1783 and lasted 8 months and corresponded to the largest outpouring of lava in recorded history (roughly 15 km^3), a value larger than Tambora or Krakatau's (Boer and Sanders, 2002). The predominant western and northwestern winds transported the intense plume of smoke and dry sulphurous fog over the British Isles and northern Europe (where most astronomical observations were performed), therefore limiting the capacity to observe astronomical events, as depicted by the extremely low number of observations obtained for 1784 (first vertical line in Figure 1). After an apparent small recovery in the following years (1785–1788) there is another major "hole" afterwards.

This decline is human in nature and is associated with the sociopolitical upheavals that spread over Europe shortly after the French revolution in 1789 (second vertical line in Figure 1), namely by enforcing the closure of the French Academy of Sciences in 1793 (Serres, 1989). This elimination of a key scientific institution in Europe was bound to deter many scholars (or upper-class citizens) to continue their regular scientific activities, including astronomical (and meteorological) observations. Despite the obvious impact of these two factors, we acknowledge that additional causes are required to explain the earlier drop in the number of observations (1777–1782).

In summary, we believe that these two additional constraining factors played an important role in limiting the number of observations, and have to be taken into account to explain the absolute minima found in 1784, 1790 and 1792, years where only German observations are registered.

We must stress that the lack of observations in the late 18th century is not a superfluous issue, as it not only roughly corresponds to a secular minimum of solar activity (Dalton minimum) but also because of the unusual length of cycle number 4 between 1784 and 1798 (Vaquero, Trigo, and Gallego, 2005). This can be either regarded as a 14-year-long cycle (peak-to-peak) or two consecutive unusually short cycles (Usoskin, Mursula, and Kovaltsov, 2003), implying the existence of a so-called "lost" solar cycle. Whatever the case, the fact remains that this period was badly covered in terms of observations (Figure 1), and also, that the cycle of solar activity exhibited a highly unusual pattern of behaviour between 1784 and 1798. Therefore, it is within this context (a severe decline of sunspot observations between 1777 and 1795 and the unusual solar activity between 1784 and 1798) that we stress the significance of the relatively high number of "new" geomagnetic and auroral observations performed by Sanches Dorta in the southern Hemisphere (Vaquero and Trigo, 2005a).

The main objectives of this paper are (1) to add a considerable number (49) of potential southern hemisphere aurora australis observations from Rio de Janeiro between 1781 and 1788, and (2) to identify some potential intense solar storms based on the simultaneous occurrence of auroral events and large changes of daily geomagnetic declination values.

2. Geomagnetic and Auroral Observations

Bento Sanches Dorta was a Royal Astronomer for the Portuguese Kingdom who performed frequent meteorological and astronomical observations in Rio de Janeiro (Brazil, a Portuguese colony at the time) between 1781 and 1788 (Carvalho, 1985). He performed an enormous amount of geomagnetic declination (GD, hereafter) observations (circa 20000) and aurora observations during this period. Therefore, we want to contribute to the study of solar activity, using a wealth of new data obtained through an 8-year-long period, located within the late 18th-century window that suffers from lack of observations. This work uses extensively the observations of GD and available aurora records from the articles that Sanches Dorta published in the *Memorias da Academia Real das Sciencias de Lisboa* (Sanches Dorta, 1797, 1799a,b, 1812a,b,c).

Sanches Dorta used a fairly simple compass to perform his observations. Concerning the measuring methodology, we know that Sanches Dorta performed his observations with great regularity at fixed hours, namely at 6, 10, 12, 14, 16 and 18 h for the entire period, and since 1785, also at 20 h (Vaquero and Trigo, 2005a). The existence of a daily cycle for GD had been discovered recently by G. Graham (Stern, 2002); this fact has prompted many observers to produce hourly measurements throughout the day. Despite the large quantity of individual observations performed by Sanches Dorta only a relatively small sub-set of aggregated data has reached the present time.

Bento Sanches Dorta was a keen observer interested in all relevant meteorological and astronomical events. Therefore, it is only natural that besides temperature, precipitation, cloud cover, fog and geomagnetic declination he registered all auroral observations that he had the opportunity to witness (*e.g.* Vaquero, Trigo, and Gallego, 2005; Vaquero and Trigo, 2005a). Table I shows the main characteristics of the 49 aurorae considered, including the observation day and the document source.[1] Finally, the last column depicts the original comments by Sanches Dorta on that specific episode. Unfortunately, Sanches Dorta's aurora observations were relatively unsophisticated, most of the times his recordings do not include relevant details such as azimuth and colour. The relatively large number of episodes of aurora australis recorded by Sanches Dorta is striking, particularly if one takes into consideration the low geomagnetic latitude of Rio de Janeiro. Nevertheless, at least four different types of low-latitude aurorae have been described in literature (Rassoul *et al.*, 1993). Interestingly, a recent comprehensive report on the appearance of aurorae at lower latitudes, and during periods of relatively low solar activity, stresses the necessity of the science community to address these sparsely described phenomena (Silverman, 2003).

To estimate the geomagnetic latitude ϕ over the last four centuries we have used the equation $\tan \Phi = (\tan I)/2$, where I is the geomagnetic inclination. To calculate I we have used the global geomagnetic model gufm1 developed, and kindly provided, by Jackson, Jonkers, and Walker (2000). The secular variation of geomagnetic latitude of Rio de Janeiro can be seen in Figure 2 and it confirms the very low (and declining) values throughout this period implying a correspondingly low probability of aurora occurrence. For the period under consideration in this paper, the geomagnetic latitude for Rio was approximately 10°S.

How close to the geomagnetic equator can aurora be observed? Silverman (1995) studied reports of aurora sightings in Singapore during the great storm of 25 September 1909. He concluded that the reports of visual aurora were due to a confusion of storm effects on telegraph and cable communications close to Singapore with real aurora observations at higher latitudes. However, more recently, Silverman and Cliver (2001) analysed and gave credit to a report of a very-low-latitude aurora from the magnetic observatory at Apia, Samoa (10°S geomagnetic latitude) during the great magnetic storm of 14–15 May 1921. Thus, aurorae can be

[1]The large number of aurorae recorded by Sanches Dorta implies an average frequency of seven aurorae per year, a rate more typical of stations located at mid-geomagnetic latitudes. We were surprise by these high number of low-latitude sightings. Therefore, we are aware that it is necessary to take all the precautions when using the data shown in Table I. The absence of artificial light pollution and a possible lack of knowledge of other phenomena could explain, at least partially, why Sanches Dorta would do erroneous interpretations of his observations. In particular, registering as an auroral event phenomenon when in reality was occurring airglow, noctilucent clouds, reflection of the light of the moon in cirrus, etc. In reality, we do not believe that a keen observer such as Sanches Dorta could commit such gross error continuously. Nevertheless, we felt that we should keep as faithful as possible to the entire data set recorded by Sanches Dorta.

TABLE I

Aurorae observed by Sanches Dorta from Rio de Janeiro.

Year	Dates	Source	Descriptions
1781	22 and 25 July; 15 and 19 Dec	Sanches Dorta (1797)	No descriptions available
1782	20 February; 27 November; 3, 4 and 31 December	Sanches Dorta (1797)	No descriptions available
1783	1, 3 and 29 January; 24 February; 4 and 8 March; 27 April; 30 September; 22 October	Sanches Dorta (1797)	Most of them with weak light
1784	7 and 25 July; 10 August; 30 December	Sanches Dorta (1799a)	[7 July] Weak light; [25 July] very luminous; [10 August] very luminous; [30 December] weak light
1785	20 August		Extremely bright. Started very luminous, it spread through the entire hemisphere and looked so brilliant that appeared to be on fire: the planets that were located near the horizon looked like incandescent iron; the aurora started at 2:25 a.m. and ended with the daylight
	29	Sanches Dorta (1799b)	Extremely bright. During the night the entire hemisphere was set alight again: but it was even more intense in the morning
	31		Extremely bright. On the 31st of the same month a reddish aurora australis started at 1:28 a.m. slowly increasing its size, culminating in a very luminous "bonfire" at more or less 30° high; and it remained for 20 min: afterwards it started to decrease and finished completely at 2:20 a.m.
1786	7, 9, 27 and 28 February; 18 and 19 March; 9 April; 26 June; 2 July; 16 and 23 August; 15 October; 13, 14 and 25 November; 16 December	Sanches Dorta (1812a)	From these 16 aurorae australis that I have witnessed, 9 were very bright, particularly the one on 26 June, that started at 2:12 a.m. and ended with daylight: the remaining 7 were weak in light
1787	7 and 23 February; 11 March; 6 and 13 April; 19 June; 31 October	Sanches Dorta (1812b)	All these aurorae episodes were weak of light, and some of them finished while intense storm (with lightning) strikes at the opposite side
1788	9 May	Sanches Dorta (1812b)	A weak aurora australis started at around 6:15 p.m. and ended by 7:40 p.m.

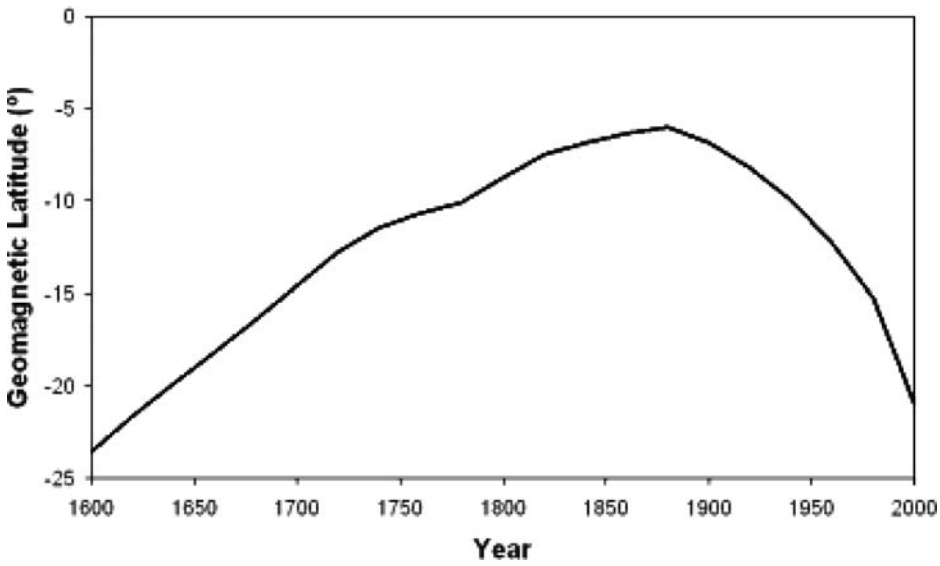

Figure 2. Time evolution of the geomagnetic latitude of Rio de Janeiro from the geomagnetic model gufml by Jackson, Jonkers, and Walker (2000).

observed closer to the geomagnetic equator in some occasions during great magnetic storms.

Despite the aforementioned precautions with Sanches Dorta's data set, we do not doubt that a fraction of the 49 aurorae registered in Table I by Sanches Dorta do correspond to low latitude real aurorae, perhaps not detectable for a person without scientific training, but recognizable by an experienced observer such as Sanches Dorta. Besides, we want to stress two additional favourable points, namely (1) one of the aurora events corresponds to an observation of a potential conjugated aurora simultaneously observed in Lisbon and Rio, and (2) in some cases, there is a clear relationship between the timing of the observation of an aurora and abrupt variations of the GD values registered by Sanches Dorta. In the following sections we will further analyse these cases with more detail.

Vaquero and Trigo (2005b) have compiled 18 aurorae observed in Portugal in late 18th century by Jacob Prætorius, a German scientist resident in Portugal. From this list we can verify that the southern (australis) aurora observed by Sanches Dorta on 27 April 1783 was coincident with a northern (borealis) aurora observed in Lisbon, by Jacob Prætorius on the very same day (Prætorius, 1785). Therefore, in this episode, we are particularly confident of the quality of the observations performed by both (Sanches Dorta and Prætorius), as their independent observation of auroral lights on that day supports one another (in spite of the lack of any reference to each other on this fortunate coincident observation). Based on the geomagnetic model of Jackson, Jonkers, and Walker (2000) the geomagnetic latitude of Lisbon

and Rio de Janeiro was, approximately, 42° and −10° respectively. It should be emphasised that the simultaneous observation of aurora lights in Lisbon and Rio de Janeiro gives a clear indication that a powerful solar storm occurred shortly prior to this date. Unfortunately, we do not have daily values of the GD field registered by Sanches Dorta for the year 1783, a fault that limits a more in depth characterization of this event.

3. Auroral Observations and Variations of Compass

As stated earlier in the paper, Sanches Dorta performed a wide range of astronomical and meteorological measurements including several daily observational readings of the GD in Rio de Janeiro. Authors looking for a more comprehensive analysis on the measurements performed by Sanches Dorta and actual GD data are referred to Vaquero and Trigo (2005a).

Recently, Willis *et al.* (2005) used a comprehensive collection of catalogues of ancient sunspot and auroral observations from East Asia to identify possible intense historical geomagnetic storms in the interval 210 BC–AD 1918. Using a similar approach, we intend to compare the dates of occurrence of aurorae and the GD data recorded by Sanches Dorta. We have been able to find four cases in which there is a very clear relation between the observation of aurorae and abrupt variations of the compass observed by Sanches Dorta. In these cases, we try to assess the corresponding daily values of the Group Sunspot Number (GSN; Hoyt and Schatten, 1998). Unfortunately, there are many gaps on the daily time series of GSN, which undermines its use. Finally, it shows that we could not carry out the comparison with the daily values of the International Sunspot Number (or Wolf number), as these daily values are only available since 1818.

3.1. 7–9 February 1786

Time series of GD (registered by Sanches Dorta) and GSN values (whenever available) between 29 January and 24 February 1786 are shown in Figure 3. Two aurorae episodes were observed on 7 and 9 February 1786. The occurrence of the two aurorae coincides in time with a strong positive deviation of the GD, while the GSN is characterised by the appearance of a relative maximum in February 14 (70) immediately followed by an abrupt descent of GSN counts to values closer to 20.

Interestingly, Sanches Dorta himself was sensitive to this coincidence and addresses the clear relation between them in one of his works: "A Maior declinação Oriental, que a Agulha magnetica mostrou em todo este anno, he 6°. 50′ no dia 8 de Fevereiro as 2 h. da tarde, [. . .] succedeo hum día depois d'Aurora Austral luzente, que principiou ás 11h. 8′ da noite do dia 7: e tambem antes da outra Aurora que começou ás 2 h. 45′ da manhã do dia 9 do dito mez" (Sanches Dorta, 1812a,

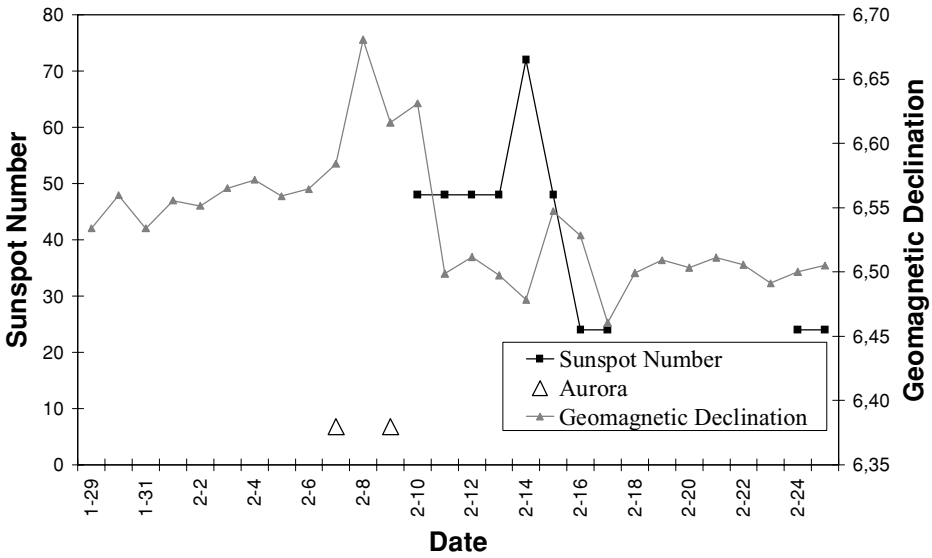

Figure 3. Daily variability of Group Sunspot Number (GSN) and geomagnetic declination between 29 January and 24 February 1786. The two *triangles* represent the two auroral episodes observed on 7 and 9 February 1786.

p. 77). "The largest eastern declination shown by the magnetic needle throughout this year was 6°. 50′, on the 8th of February at 2 pm, [. . .] this took place one day after the diffuse austalis aurora, that started at 11 h and 8 min (pm) observed on the 7th: it also occurred one day before another aurora that started at 2 h 45 min (am) on the 9th of that very some month."

3.2. 11 March 1787

On 11 March 1787, Sanches Dorta observed an aurora (triangle in Figure 4). Time series of GD and GSN values (whenever available) between 25 February and 23 March 1787 are also represented in Figure 4. In this case, the aurora observed from Brazil occurs 1 day after an abrupt increase of the GD, while the available GSN is low 1 day after the appearance of aurora (12–13 March) and increases considerably a few days later (20 March). We should stress again that the original available information to derive the GSN in these years is very poor, a fact that undermines its use for comparison purposes.

Again in this case, Sanches Dorta pointed out the relation between the two phenomena: "A Maior declinação Oriental, que a Agulha-magnetica mostrou em todo este anno, he de 6°. 53′ no dia10 de março ás 2 h. da tarde, [. . .]. Hum dia antes de huma aurora luzente, que começou ás 7 h. 30′, e acabou ás 9 h. 10′ da noite" (Sanches Dorta, 1812b, p. 116). "The largest eastern declination shown by

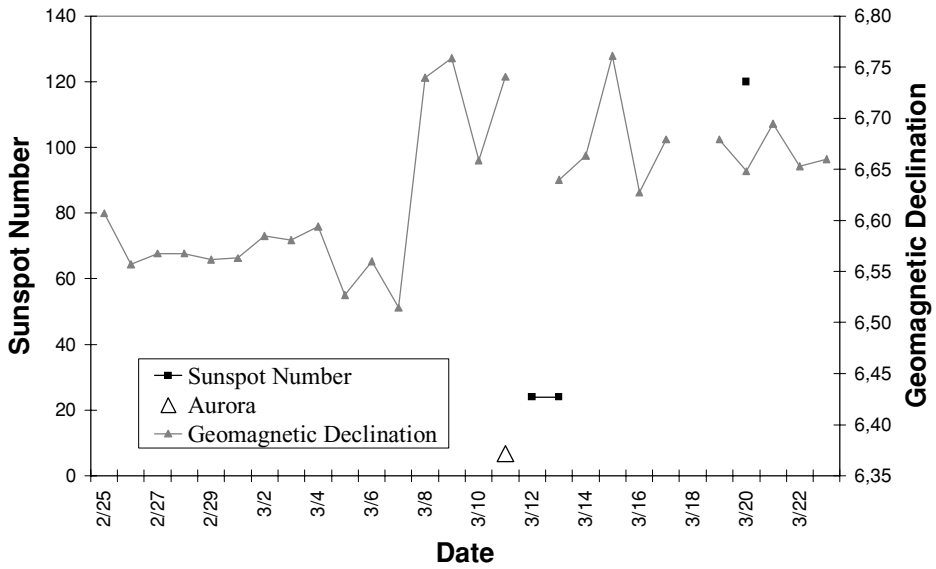

Figure 4. Daily variability of Group Sunspot Number (GSN) and geomagnetic declination between 25 February and 23 March 1787. The *triangle* corresponds to the aurora episode observed on 11 March 1787.

the magnetic needle throughout this year was 6°. 53′, on the 10th of March at 2 pm, [. . .] one day before a diffuse aurora, that started at 7 h and 30 min (pm) and finished at 9 h and 10 min (pm)."

3.3. 31 October 1787

Time series of GD and corresponding GSN values (whenever available), between 8 October and 21 November 1787 are shown in Figure 5, a temporal window centred on 31 October, when an aurora was observed by Sanches Dorta. In this case, the GSN index is useless because there is only data for 1 day, 3 weeks after the observation of the aurora. Nevertheless, it is almost impossible not to appreciate the coincidence between a very abrupt change in the GD and the occurrence of the aurora of 31 October 1787.

3.4. 9 May 1788

Figure 6 shows the GD registered by Sanches Dorta, and the available daily values of the GSN index between 11 April and 23 May 1788. Sanches Dorta observed an aurora on 9 May 1788. In this episode, we appreciate again that the aurora occurs after an abrupt change of the GD, in this case an abrupt descent, while the available data of the GSN kept an apparent constant medium-high value, which provides

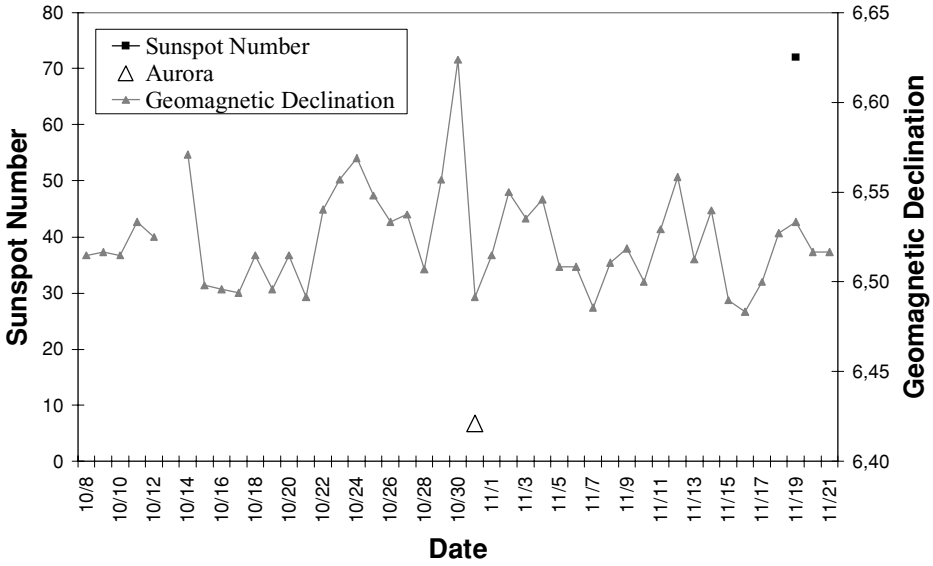

Figure 5. Daily variability of Group Sunspot Number (GSN) and geomagnetic declination between 8 October and 21 November 1787. The *triangle* corresponds to the aurora episode observed on 31 October 1787.

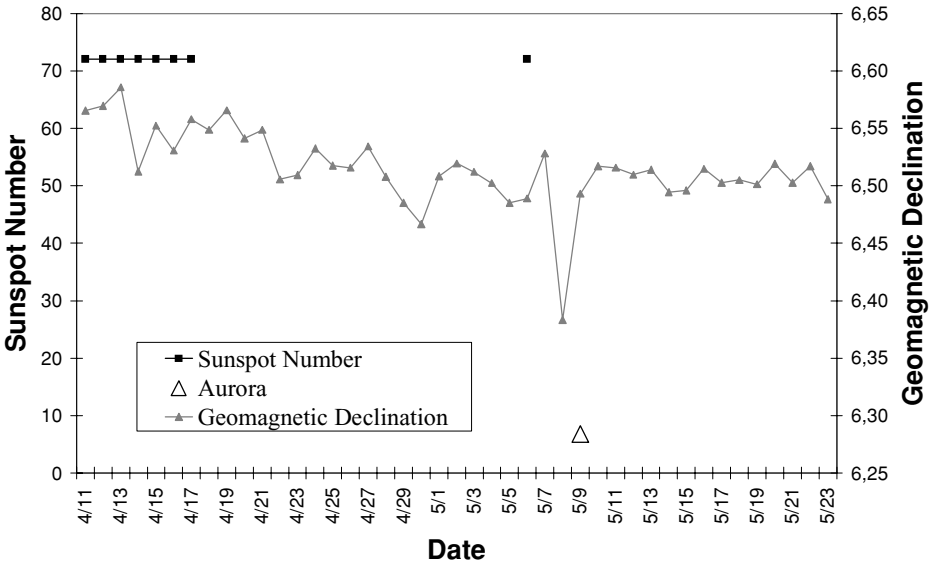

Figure 6. Daily variability of Group Sunspot Number (GSN) and geomagnetic declination between 11 April and 23 May 1788. The *triangle* corresponds to the aurora episode observed on 9 May 1788.

little information. Unlike in the two previous examples, Sanches Dorta described this aurora without relating it to the strong descent of the GD: "As 5 h. 10′ da manhã deste dia [9 de mayo de 1788] houve huma Luz-Zodiacal, e á noite pelas 6 h. 15′ começou huma Aurora Austral pouco luzente, que acabou ás 7h. 40′" (Sanches Dorta, 1812c, p. 167). "At 5 h.10 min am of this day [9th of May 1788] there was a zodiacal-light, and then at night (pm), around 6 h. 15 min a faint australis aurora started and finished at around 7 h and 40 min." Nevertheless, this comment stresses Sanches Dorta's ability to perfectly distinguish an aurora from the fainter zodiacal light.

4. Conclusions

The solar activity in the late 18th century is poorly known. From the large number of geomagnetic and auroral observations undertaken by Bento Sanches Dorta in Rio de Janeiro (Brazil) for the period 1781–1788, we highlight four large solar storms that occurred approximately on 7–9 February 1786, 11 March 1787, 31 October 1787 and 9 May 1787. The daily monitoring of geomagnetic declination from 1784 onwards was a factor of paramount importance to validate these four events. Unfortunately, the vast majority of the remaining 45 auroral sightings described by Sanches Dorta lack a similar corroboration. It should be stressed that none of these events occurred in the years of 1784, *i.e.* during the minimum of the 11-year cycle of solar activity. It is clear that the following year of 1785 registers already a considerable number of sunspots, particularly the second half of 1785 (Vaquero, Trigo, and Gallego, 2005), enclosing the three August solar storm described by Sanches Dorta (Table I).

Naturally, it is necessary to be cautious with the large number of episodes of aurorae described by Sanches Dorta, taking into consideration the low geomagnetic latitude of Rio de Janeiro at the time ($\sim 10^\circ$S). However, it is now recognised that low-latitude aurorae are more frequent than previously thought (Silverman, 2003). Recent papers have provided new long-term catalogues of low-latitude aurorae over different sub-artic areas, such as Southern Europe (Vaquero, Gallego, and García, 2003), Japan (Nakazawa, Okawa, and Shiokawa, 2004) and North America (Silverman, 2003). In fact, the characteristics of the four most usual types of low-latitude aurorae have been well described in the literature (Rassoul *et al.*, 1993). Unfortunately, the simplistic nature of the auroral descriptions provided by Sanches Dorta makes it particularly difficult to ascribe each aurora to a specific category. Nevertheless, some of the most intense, mostly reddish and very long-term aurorae seem to fit the SAR (Stable Auroral Red arc) type (Rassoul *et al.*, 1993). This is the case of the three events on 20, 29 and 31 August 1785 that were described in much greater detail than most of the remaining aurorae observed by him (Table I).

Finally, it should be stressed that Rio de Janeiro is located almost in the centre of the very pronounced negative geomagnetic anomaly of the southern Atlantic, where

the magnitude of the surface field is considerably lower than 20,000 nT (Merril, McElthinny, and McFadden, 1998). Secular trends since 1789s have not altered the location and magnitude of this anomaly significantly. It should be stressed that this large geomagnetic anomaly implies that the Van Allen Belts present their closest approach to the Earth's surface over this region of the globe, descending from an average high of 700 miles to just 120 miles. Therefore, it is more likely that, during particularly intensive solar activity, highly energised particles reach the ionosphere over this region of the globe rather than other regions located at similar geomagnetic latitudes.

We believe that this work can also act as a warning to the relatively limited information that daily standard indexes of solar activity for this period (based on observations of sunspots) are capable of achieving. Therefore, it is important that more colleagues direct part of their efforts to the locating of older observations of sunspots and geomagnetic data in order to improve the reliability of solar variability, in general, and sunspot numbers in particular, during these epochs.

Acknowledgments

This work has made use of the Group Sunspot Number provided by the *NOAA/ National Geophysical Data Center*. This research has made use of the Astrophysics Data System (NASA). All the historical material used in this work was consulted at the *Biblioteca da Academia das Ciências de Lisboa* and at the *Biblioteca Nacional de Lisboa*. J. M. Vaquero was partly supported with a grant by the *Gulbenkian Foundation* and *Biblioteca Nacional de Lisboa*. The authors are in debt to Andrew Jackson (Univ. Leeds, UK) for providing us access to the Geomagentic database as well as to the *gufm1* model.

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