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ON THE CONNECTION BETWEEN SOLAR ACTIVITY AND LOW-LATITUDE AURORAE IN THE PERIOD 1715 – 1860

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Abstract. Observations of aurorae borealis at low latitudes are very rare and are clearly associated with strong geomagnetic storms. Morphologically, they are characterized by a diffuse red colour with no rapid motions. The main aim of this paper is to analyse two hitherto ignored aurorae that were observed at two low-latitude sites, Tenerife (28°N 18°W) and Mexico City (19°N 99°W), in 1770 and 1789, respectively. These observations can give supplementary information about the level of solar activity at those times where direct solar observations were rather scarce. Studying also the behaviour of the heliosphere during this period using different proxies, we find that the open magnetic field better describes auroral occurrences. The variation over time in geomagnetic latitude at the two sites is also calculated.

1. Introduction

Solar variability is manifested on different time scales, depending on the type of energy dissipated. On the scale of centuries, the magnetic energy dominates and in a schematic way we can divide the effects on our planet into two different channels, depending on the topology of the magnetic field.

(a) *Radiation domain:* The magnetic flux of the active regions (hereafter closed magnetic fields, CMFs), characterized by magnetic configurations with closed field lines dominating the variations in the total irradiance and emission in the high-energy range of the solar spectrum (ultraviolet and X-rays). Most of the radiative losses from the outer layers occur in these regions.

(b) *Particles domain:* Large-scale magnetic regions have field lines open toward the interplanetary medium. They are the main source of a continuous outward flow of charged particles (protons, electrons and He nuclei) known as the solar wind. The solar magnetic field of the open regions (OMFs) is frozen into this wind, configuring the interplanetary magnetic field (IMF), which produces a huge magnetic region, the heliosphere, which fills practically the whole Solar System. Galactic cosmic rays (hereafter GCRs) are high-energy particles (mainly protons with energies in the range 1 – 20 GeV), originating outside our planetary system and striking the Earth from all directions. Both the flux and energy spectrum of GCRs are modulated by the strength of the heliosphere, being stronger when the IMF is weaker. Variations in the solar wind are produced by transient events, such as coronal mass ejections, and the recurrent passage of equatorial coronal holes.

Aurorae are linked to the particle domain, and their brightness and large angular size have attracted the interest of many civilizations, with deep roots in mythology. Numerous non-scientific documents have reported these events, and we can make use of them as a proxy of solar activity in past times (*e.g.* Siscoe, 1980; Willis and Stephenson, 2002).

Observations of aurora borealis at low latitudes are rare, and are clearly associated with strong geomagnetic storms. However, Silverman (2003) mentions several cases of low-latitude aurorae during periods of quiet to moderate solar activity. Morphologically, they are characterized by a diffuse red colour (produced by the 630 nm oxygen emission) with no rapid motions. Silverman (1995) establishes a threshold magnetic latitude of about 15° for a visual auroral event. Rassoul *et al.* (1993) proposed a classification of low-latitude aurorae based on O I 630/558 ratios.

Stable auroral red (SAR) arcs are also often observed at subauroral latitudes, predominantly during the recovery phase of magnetic storms (Rees and Roble, 1975) lasting for more than ten hours. They are are produced by electron heating in the upper F-region of the ionosphere. Modern monitoring of airglow lines can be used to study the physical characteristics of low-latitude aurorae and SARs. Shiokawa, Ogawa, and Kamide (2005) conducted such a study in Japan during the period 1999 – 2004.

McCracken *et al.* (2001a,b) have identified 125 solar proton events (SPEs) having energies greater than >30 MeV and a fluence greater than 10^9 proton cm^{-2} in the nitrates of Artic and Antartic ices during the period 1561 – 1950. McCracken *et al.* (2004b) found an inverse dependence between the probability of observing large SPEs and the strength of the interplanetary magnetic field derived from empirical predictions.

Table I lists the most important catalogues of low-latitude aurorae, and Table II lists some detailed studies on individual events. After the International Geophysical Year in 1957, the number increased due to automatic monitoring programmes and the higher sensitivity of the detectors.

TABLE I
List of sources about low-latitude aurorae.

	Period	Number of aurorae	Location
Vallance Jones (1992)	1591–1938	12	Summary great aurorae
Vaquero, Gallego, and García (2003)	1700 – 1855	39	Iberian Peninsula
Nakazawa, Okada, and Shiokawa (2004)	1150 – 1860	16	Japan
Vaquero, and Trigo (2005)	1781 – 1793	18	Portugal
Meinel, Negaard, and Chamberlain (1954)	1897 – 1951	1267	Yerkes observatory

TABLE II
Studies of individual low-latitude aurorae in chronological order.

Date	Location	Reference
25 January 880	North of Africa	Vaquero and Gallego (2001)
27 April 942	South of Spain	Vaquero and Gallego (2001)
August 816 – July 817	Yemen ∼16°	Basurah (2005)
October – November 1203		Basurah (2005)
January 1321 – January 1322		Basurah (2005)
26 August 1449		Basurah (2005)
28 August 1859		Loomis (1861)
25 September 1909		Silverman (1995)
14 – 15 May 1921	Apia (Samoa) 13°S	Silverman and Cliver (2001)
25 – 26 January 1938	Portugal, Morocco	

Three of the aurorae reported by Basurah (2005) have no dates of observation.

The first aim of this paper is to test the better activity indexes related with the number of low-latitude aurorae. We will concentrate on the period 1720 – 1850. The starting time is marked by the recovery of solar activity after the Maunder Minimum, and the ending by the coincidence of such events as the discovery of solar cycle (1845), the observation of the white-light flare by Carrington (1859) and the start of regular geomagnetic measurements (Index *aa* 1868); that is, the availability of more modern sources of information on this topic. We shall then proceed to a detailed study of two aurorae observed at two low-latitudes sites: Tenerife (28°N 18°W) and Mexico City (19°N 99°W). These can offer supplementary information about the level of solar activity at those times when solar observations were rather scarce (Hoyt and Schatten, 1998a,b).

TABLE III

Sources of auroral observations during the period 1720 – 1855.

Reference	Latitude range
Krivsky and Pemjl (1988)	<55
Broughton (2002)	55 – 65
Mairan (1733)	
Schröder (2003)	

2. The Level of Magnetic Activity

Obviously, the level of solar activity plays a decisive role in the formation of aurorae. Here, we will compare the mentioned low-latitude aurorae with the most suitable index representing the temporal behaviour of solar activity: the sunspot number and a simulated proxy of the heliospheric magnetic field.

The 18th century marked the recovery of the solar activity after the Maunder Minimum. The number of reported aurorae increases dramatically not only due to this objective fact, but also due to the seminal works of Halley (1716) and Mairan (1733), and certain social factors (Table III).

Krivsky and Pemjl (1988) have compiled a catalogue[1] recording the aurorae visible in Europe in the period 1715 – 1850 at latitudes lower than 55°. They assumed that nearly all the aurorae were recorded roughly after 1720 and that therefore no normalization factor need be applied.

Lockwood, Stamper, and Wild (1999) and Lockwood (2003) have derived the intensity of the interplanetary magnetic field from the *aa* geomagnetic index, a record that extends back to 1868. They found that the average strength of the solar magnetic field has doubled in the last 100 years. Usoskin *et al.* (2002b) simulated variations of the OMF with a model based on the emergence and decay rates of active regions (Solanki, Schüssler, and Fligge, 2002) that fits reasonably well with other proxies of solar activity, such as the ^{10}Be records in ice cores.

Figure 1 compares two parameters of solar activity with different sources of auroral observations from 1720 to 1855.

A double peak in the geomagnetic records has been observed with the two maxima: (i) shortly before the sunspot maximum and produced by transient events, and (ii) two years after the maximum produced by both transient and recurrent events. Geomagnetic activity is higher in the second half of the even-numbered cycles and in the first half of the odd-numbered cycles, giving rise to a 22-year variability (Chernosky, 1966; Vennerstron and Friis-Christensen, 1996).

[1] `ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA`

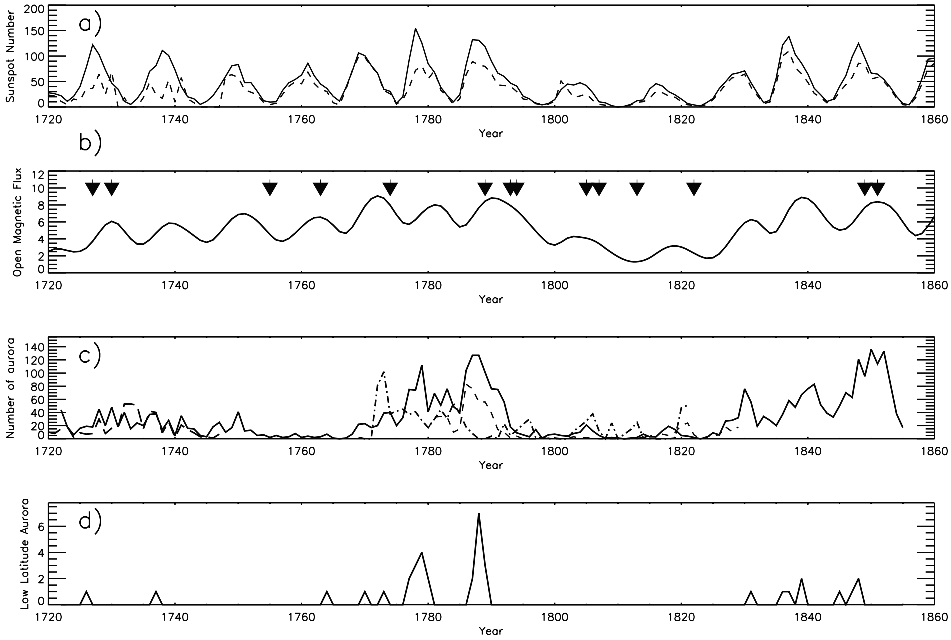

Figure 1. (a) Variation of the closed magnetic field (CMF), indicated by the sunspot number; (b) open magnetic flux (*bottom*), calculated by Usoskin *et al.,* (2002b) (data courtesy of M. Schüssler, MPIfA, Germany). *Arrows* indicate the SPEs reported by McCracken *et al.* (2004a); (c) (*solid line*) yearly number of aurorae in the catalogue of Krivsky and Pemjl (1988), (*dashed*) Schröder data during the Dalton Minimum, (*dashed-dotted*) Canadian observations by Broughton (2002) and (*long dashes*) Mairan (1733) complemented by Viera y Clavijo (1770); and (d) a summary of low-latitude ($<42°$) aurora, observed mainly at the Iberian Peninsula.

Fritz (1873) was the first to report that the maximum of auroral sightings lags behind the sunspot maximum. Later, Maunder (1905) raised doubts about the correlation between the sunspot numbers and the appearance of aurorae. This connection was studied by Ohl and Ohl (1980), who found that the frequency of auroral occurrence at high latitudes during the declining portion of one solar cycle seems to be related to the sunspot number at the following maximum and the rapidity with which the solar activity returns to maximum (the rise time). Schlamminger (1992) has studied these lags for the Middle Ages.

Recently, Willis *et al.* (2005) have compared catalogues of ancient naked-eye sunspot and auroral observations and have tried to identify intense geomagnetic storms.

Additional information can be obtained from the abundance of cosmogenic isotopes, such as ^{14}C and ^{10}Be (Figure 2). They are produced by the action of cosmic rays and are therefore inversely related with solar activity, namely with the strength of the interplanetary magnetic field. The temporal lag of ^{14}C with respect to the sunspot number is due to the long attenuation time for ^{14}C.

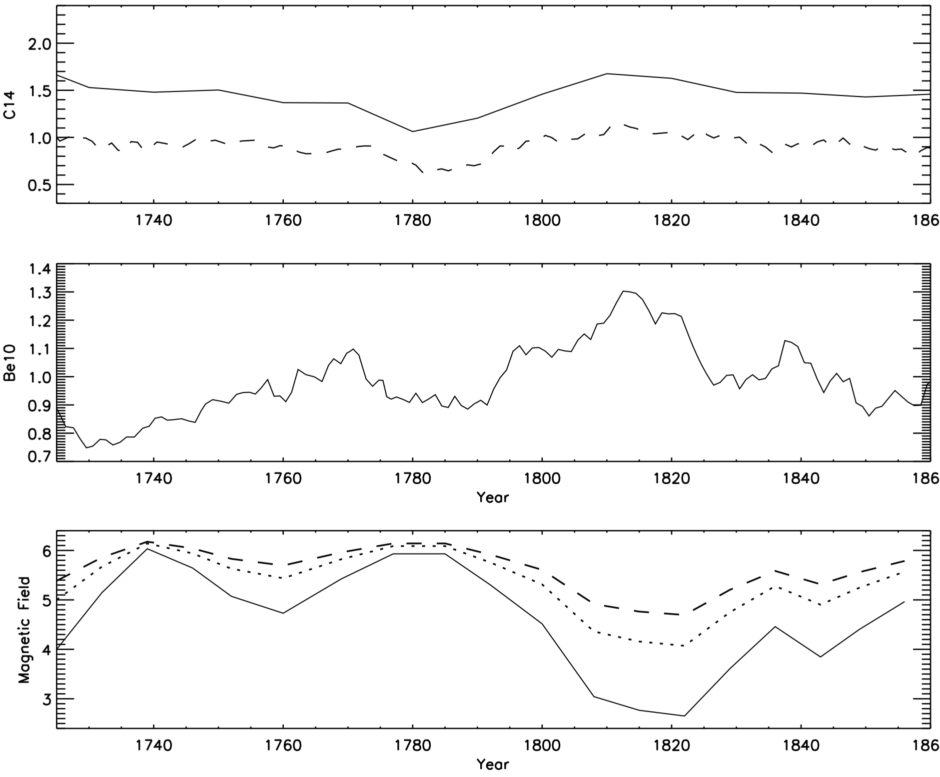

Figure 2. (Top) Plot of the ^{14}C records for two different calibrations (data courtesy of J. Beer); (Middle) plot of the ^{10}Be records (data courtesy of J. Beer); (Bottom) interplanetary magnetic field for there different relations between the diffusion factor (κ) and the heliospheric magnetic field (B) (data courtesy of R. Caballero-López).

Two ^{14}C records are plotted in Figure 2. The first is based on the Reimer (1998) calibration and the second by Stuiver and Braziunas (1993). From these records the heliospheric magnetic field has been inferred (Caballero-Lopez *et al.,* 2004) as has the long-term cosmic-ray modulation (McCracken *et al.*, 2004a) since 850 AD. A crucial point for this calculation is to estimate the diffusion properties of cosmic rays inside the heliosphere. In the lower plot of Figure 2, we represent the heliospheric magnetic field for three different values of the diffusion transport coefficient: (i) $\kappa \propto 1/B$, a relation often used in modulation work during the solar cycle, (ii) $\kappa \propto 1/B^2$, representing a measure of the stronger importance of large-scale transient events, such as CMEs, and (iii) $\kappa \propto 1/B^3$, where the modulation with the solar activity is driven most strongly by CMEs and much less by the global value of the heliospheric field (B).

Several phases can be distinguished in these figures:

(i) Recovery from the Maunder Minimum (1715 – 1765): no clear correspondence is found between the number of aurorae and the solar activity indices.

(ii) First period with enhanced activity (1765 – 1795): all parameters show high values but curiously the maximum number of aurorae is not coincident with any maximum of CMF or OPF. The 1771 – 1813 diary of Thomas Hughes from Stroud, Gloucestershire (51.75°N, 2.22°W), lists 71 nights on which the aurora was seen, between 19 February 1771 and 13 October 1805 inclusive. Ninety percent of Hughes' aurora observations occurred between 1771 and 1789 (Harrison, 2005).

(iii) The Dalton Minimum (1795 – 1823): a period of reduced activity. Usoskin *et al.* (2003) have studied in detail the beginning of this period, proposing the existence of a weak additional period from 1792 to 1794. This seems also to be supported by the auroral frequency during this interval (Usoskin, Mursula, and Kovaltsov, 2002a).

(iv) Second period with enhanced activity (1823 – 60): it was the start of a continuous increase of solar activity lasting until the present. Again we find good correlation between aurorae and activity indices. Lang (1849), Governor of St Croix, reported the sight of a red aurora at this site located at 17°44'32" North on 17 November 1848.

3. Detailed Study of Two Low-Latitude Aurorae

3.1. THE SOLAR ACTIVITY ENVIRONMENT

In this section, we describe in detail two reports about low-latitude aurorae, which have been ignored in geophysical literature although they were included in the catalogue of Krivsky and Pemjl (1988). They were observed in La Laguna (Tenerife) and Mexico City in 1770 and 1789, respectively.

The events correspond clearly to a period of enhanced solar activity as seen in Figure 3, although no sunspots were observed by the naked eye around the date of the aurorae (see the catalogue of A. Wittmann, available at the National Geophysical Data Center).

We can see that the aurorae took place in the ascending phase or close of the maximum of the solar cycle as defined by the open magnetic field. They also correspond to an enhanced period of the interplanetary magnetic field (Figure 2c).

3.2. THE AURORA OF 18 JANUARY 1770

On the night of 18 January 1770, an aurora was observed from Badajoz, a town located in the SW of the Iberian Peninsula (38°53′N, 6°58' W, 192 m). The notice is included in the manuscript entitled "Book of News", by D. Leonardo Hernández Tolosa, a priest and neighbour of the city of Badajoz, which is kept in the archives of the Cathedral of Badajoz. Several people saw that the northern part of the sky appeared red, a typical colour for low-latitude aurorae. It began at nightfall and

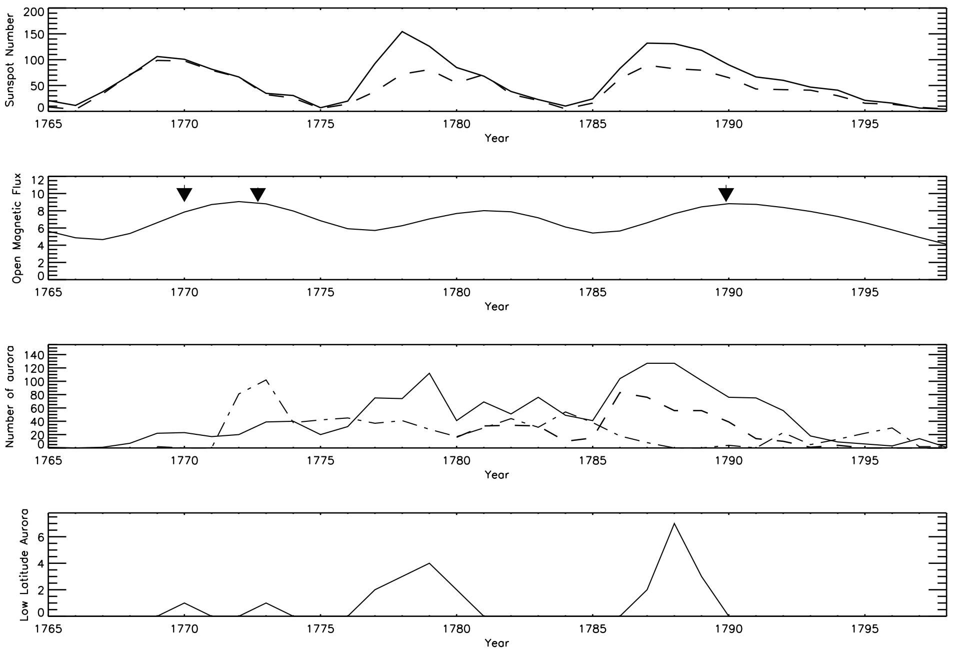

Figure 3. An enlargement of the data displayed in Figure 1 for the period 1766 – 1798. The time of the three aurorae mentioned are indicated by *arrows*.

finished at 2 a.m., approximately (see Vaquero, 2001). This aurora is also included in the catalogue of Rico Sinobas (Vaquero, Gallego, and García, 2003) as seen from Córdoba (Spain).

Further south, the historian and naturalist José de Viera y Clavijo[2] (1731 – 1813) described the aurora as seen from the city of La Laguna on the island of Tenerife with these words:

“A little more than an hour after the sunset[3] a rumour spread in the city that the Taganana mountains[4] were perhaps burning, given that part of the sky seemed to be a bright inflamed red and bathed in a vivid glow. I went out to observe the fire. But to my joy I met with a real aurora borealis. The night was cool but quiet, the clouds rather scattered and not impeding observation of the upper regions of the air, and the flamelike and blood-red hue extended all over the north from the east until a few degrees beyond the west, with a very bright light, but in no way turbulent, agitated or flickering. These aurorae borealis, in which neither flickering nor streams of bright flares are noticed, are named *quiet* or *simple* by philosophers. I should not omit to add that the very opacity of the clouds redoubled the celestial illumination, which

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[2] He used the pseudonym of Antón Guanche.

[3] Sunset on this day was at 17:28 (UT) local time.

[4] Located on the North of the island.

started to decay at some points at 11 o'clock and became completely extinguished by midnight."

Viera y Clavijo, citing the works of Halley, Mairan, and Maupertuis, suggested that the origin of such events was in the emission of radiation from the Sun. At the end of the letter he included a catalogue of auroral observations, taken mainly from Mairan (1733) but with some additions from himself (see Figure 1).

On that day, the Moon was in the last-quarter phase but below the horizon during the auroral event. The Moon rose at 00:50 UT on 19 January.

Nakazawa, Okada, and Shiokawa (2004) reported how two low-latitude aurorae had been observed in Japan in the same year 1770 (17 and 25 September), being the first aurorae especially strong and observed over a wide area.

The appearance of a second aurora in the Canary Islands on 27 October 1772 is reported briefly by Lope Antonio de la Guerra Peña in a historical account of Tenerife (De La Guerra y Peña, 2002) but lacks any morphological description.

The Canarian aurora observations took place during solar cycle number 2, from 1766.5 to 1775.5 with the maximum at 1769.7, a relatively short cycle. Our events were therefore in the decaying phase of the cycle, probably during a secondary maximum in geomagnetic activity. No daily records of sunspot numbers are available before 1818. The archive of Hoyt and Schatten (1998a,b) provides the first information about the sunspots on the disc during the 18 January 1770 event (Figure 4). C. Horrebow (Copenhagen) and J. C. Staudacher (Nuremberg) observed four groups (see also Hoyt and Schatten, 1995). This latter observer reported two groups on the disc for 27 October 1772.

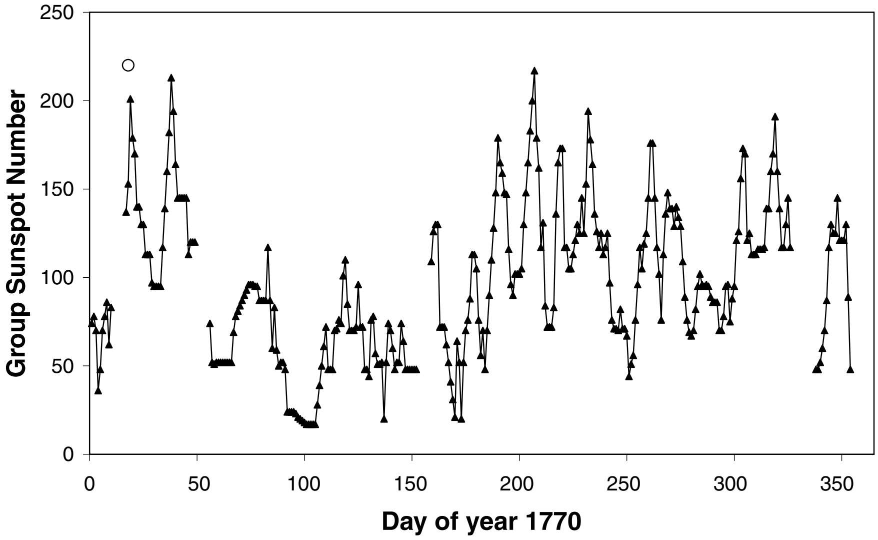

Figure 4. Variation in the Sunspot Group Number during 1770. The date of the Tenerife aurora is marked with a *circle*.

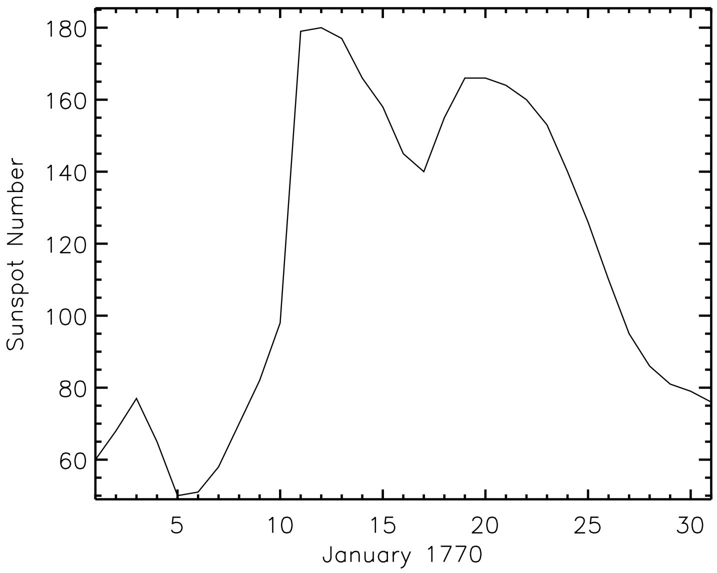

Figure 5. Variation in the relative sunspot number during January 1770 reconstructed by Letfus (1997).

Letfus (1997) reconstructed the daily sunspot number for the period 1749 – 1818 using a nonlinear two-step method of interpolation. Figure 5 shows this number during January 1770. An important increase in activity, probably produced by the emergence of a very large group, which was related with the source of the aurora is visible. No similar behaviour is associated with the 1772 aurora, which gives rise to uncertainty in the interpretation of the event.

The variation in the OMF is clearly out of phase with the sunspot number, and these aurorae occured (see Figure 3) close to the maximum of the cycle.

So far as we know, no other aurorae have been reported from the Canary Islands to this day.

3.3. THE AURORA OF 14 NOVEMBER 1789

On 14 November 1789, an aurora was observed from Mexico City and its suburbs. Due to its rarity the phenomenon had a great social impact on the inhabitants. The scientist Antonio de León y Gama (1735 – 1802) described it as very "pacific" following the classification of Mairan (León Gama, 1790):

"The aurora borealis seen at Mexico City on the night of November 14 seemed to us to be of the quiet class since we did not observe any draperies, light rays, bands or pulsations."

Moreover, León Gama collected reports from nearby villages. We will reproduce an extract of three letters. The first was written by the parish priest of Papantla, the second was written by Francisco Gutiérrez, postmaster of Real of Charcas, and the third by Bernabé de Cancela y Jerpe, also postmaster of the city of Zacatecas.

Papantla: "During the night of this day, at 20 h 15 minute, the sky being cloudless and the stars shining quite bright, it was observed that the atmosphere was illuminated north of this village from northwest to northeast in a way that gave the appearance of a huge fire on the horizon, so that many astonished people judged it to be caused by fires in the surrounding mountains. But others of a more reflective nature noticed that no smoke, the natural sign of fire, was perceived; instead, there was a diaphanous clarity, that did not impede the sight of the stars. It was so clear that there was enough light to see at distances of four leagues from this site. This brightening lasted until a quarter to ten."

Charcas: "During the night of this day, at around seven o'clock, a celestial brightening or inflammation was observed towards the north that propagated rapidly along almost the entire horizon. Its aspect was furious and ardent, forming various whitish flares, a smoke that was quite dense and thick being seen through them. It lasted about three hours."

Zacatecas: "On the 14th, at 19 h 40 minute, a bright meteor was observed to the NW, moving from north to northeast, much more glittering than fire . . . This great volume had a pyramidal column extending from the surface to the base and having in the inner part a well distinguished, diaphaneous, transparent colour, which must be a material different from the rest of this bright body, fluctuating at the beginning with different red aspects, at times more opaque, at times more brightly coloured and shining ... As far we know now, the phenomenon was seen 50 leagues from this city towards the south."

Observations of this aurora were also reported by José Antonio Alzate y Ramírez (1738 – 1799), who entered into discussion with León Gama about the character of the aurora borealis (Alzate, 1791).

The Moon was well beneath the horizon during the auroral event (rising at 2:01 local time) and sunset occurred at 17:21 (local time).

The Mexican auroral observations took place during solar cycle number 3, 1784.7 to 1798.5 with the maximum at 1788.1, a long cycle. This event was therefore located in the decaying phase of the cycle, probably during a secondary maximum in geomagnetic activity. The variation of the OMF is clearly out of phase with the sunspot number and the aurora occurs (see Figure 1) close to the maximum of the cycle. Unfortunately, there are no observations of the solar disc in the archives of Hoyt and Schatten (1998a,b) for the day of the auroral event (see Figure 6).

3.4. DETERMINATION OF MAGNETIC LATITUDES

In order to evaluate the visibility conditions of aurorae, we computed the magnetic latitudes of both Tenerife and Mexico City for recent centuries. To do this, we used a mathematical model which approximates the geomagnetic field at the epoch to

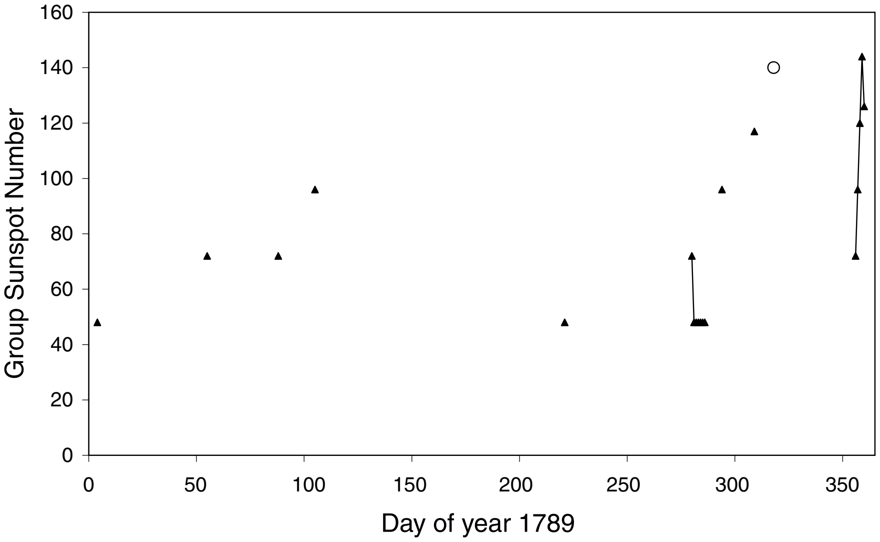

Figure 6. Variation in the Sunspot Group Number during the year 1789. The date of the aurora is marked with a *circle*.

which the analysis refers. The magnetic field is represented by an expansion in terms of spherical harmonics. This expansion is characterized by a series of spherical harmonic coefficients whose values are derived from the analysis of observed values of the elements of the magnetic field collected from survey and observatory data where these exist, and the compilation of archaeomagnetic data for ancient epochs.

Assuming a bipolar configuration for the geomagnetic field, the geomagnetic latitude, ϕ, is given by the following expression:

$$\tan\phi = (\tan I)/2,$$

where I is the magnetic inclination, a parameter to be taken from a model of the time variation of the geomagnetic field. Until the 17th century we used the model of Hongre, Hulot, and Khokhlov (1998). The compilation of magnetic measurements, which are the basis of the model, covering the 17th and 18th centuries was due to Van Bemmelen (1899) and Veinberg and Shibaev (1969). In fact, these models are a compilation of other models, being normalized with the Schimdt method using Legendre polynomials (Barraclough, 1978). A polynomial was fit to the annual values from the different models involved in the epoch of interest. Finally, the International Geomagnetic Reference Field (IGRF) model describes the evolution of the geomagnetic field in the 20th century.

Figures 7 and 8 show the variation of the magnetic latitude for Tenerife and Mexico City, respectively.

During the 18th century, Tenerife reached the highest magnetic latitude for the last 2000 years, so that the probability of seeing an aurora was increased.

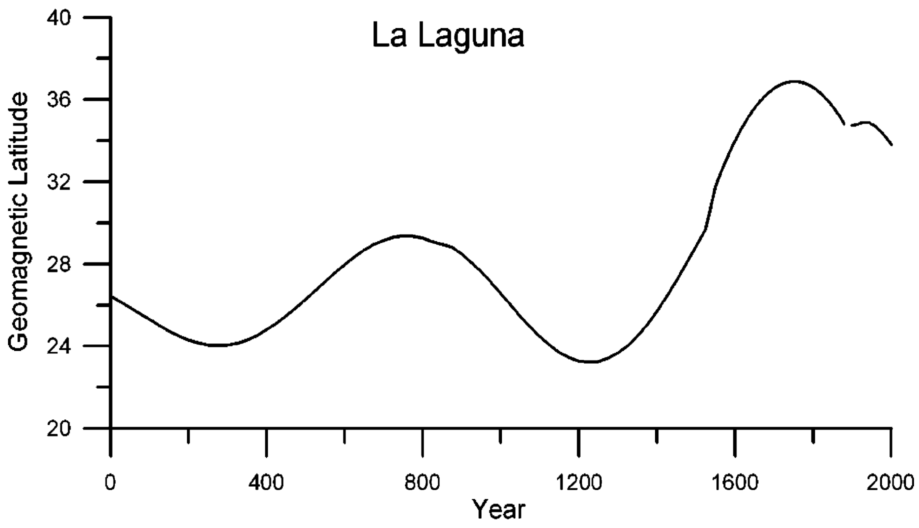

Figure 7. Long-term variation of the magnetic latitude of La Laguna (Tenerife).

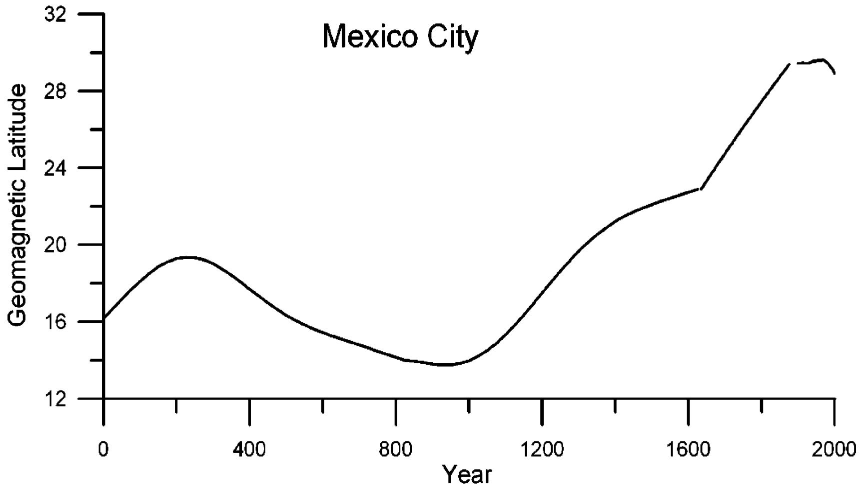

Figure 8. Long-term variation of the magnetic latitude of Mexico City.

For the 18th century, Mexico City also had the highest magnetic latitude until that epoch. However, it went on with that increasing trend so that now there is even a better chance of observing aurorae, as confirmed by the relatively large number observed there in the 20th century (Silverman and Cliver, 2001).

4. Conclusions

The relationship between the appearance of aurorae in mid- and low-latitudes and various indices describing the solar activity have been studied. The selected sample covered the period 1715 – 1860, an epoch not very well covered in the existing literature, which includes the Dalton Minimum. We have studied the aurorae visible in this period and related them to different parameters describing the physical state of the heliosphere. We confirmed that they are mainly located in the decaying phase of the solar cycle, as defined by the sunspot number. However, they coincide with the maximum of the Open Magnetic Field, a better descriptor of the physical state of the heliosphere.

Two descriptions of low-latitude aurorae were selected for more detailed study. The duration of these events allows us to conclude that they were typical discrete aurora and not stable auroral red arcs. We have shown that in the case of Tenerife the conditions for auroral visibility were the best for the last 2000 years, whereas in Mexico City the situation has continued to increase. Another important distinction is the correspondence of the Mexican aurora with one of the SPEs events reported by McCracken *et al.* (2001), whereas this was not the case for either of the two Tenerife events (1770 and 1772). This allows us to tentatively suggest a different origin for these two low-latitude aurorae.

This and other previous studies show the importance of surveying ancient documents to complement the existing data of low-latitude aurorae and solar activity in historical times.

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