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Key Points:

- Daytime lower ionosphere sensitivity to solar X-flares inferred from VLF measurements using a parameter called the minimum X-ray fluence
- The minimum X-ray fluence value shows no dependence with the size of solar flares
- Long-term minimum X-ray fluence variation correlates with the level of solar Lyman α flux and anticorrelates with the ionospheric sensitivity

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Lower Ionosphere Sensitivity to Solar X-ray Flares Over a Complete Solar Cycle Evaluated From VLF Signal Measurements

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Abstract The daytime lower ionosphere behaves as a solar X-ray flare detector, which can be monitored using very low frequency (VLF) radio waves that propagate inside the Earth-ionosphere waveguide. In this paper, we infer the lower ionosphere sensitivity variation over a complete solar cycle by using the minimum X-ray fluence (F_{Xmin}) necessary to produce a disturbance of the quiescent ionospheric conductivity. F_{Xmin} is the photon energy flux integrated over the time interval from the start of a solar X-ray flare to the beginning of the ionospheric disturbance recorded as amplitude deviation of the VLF signal. F_{Xmin} is computed for ionospheric disturbances that occurred in the time interval of December–January from 2007 to 2016 (solar cycle 24). The computation of F_{Xmin} uses the X-ray flux in the wavelength band below 0.2 nm and the amplitude of VLF signals transmitted from France (HWU), Turkey (TBB), and U.S. (NAA), which were recorded in Brazil, Finland, and Peru. The main result of this study is that the long-term variation of F_{Xmin} is correlated with the level of solar activity, having F_{Xmin} values in the range $(1-12)\times10^{-7}$ J/m^2. Our result suggests that F_{Xmin} is anticorrelated with the lower ionosphere sensitivity, confirming that the long-term variation of the ionospheric sensitivity is anticorrelated with the level of solar activity. This result is important to identify the minimum X-ray fluence that an external source of ionization must overcome in order to produce a measurable ionospheric disturbance during daytime.

1. Introduction

Very low frequency (VLF; 3–30 kHz) radio signals propagate inside the Earth-ionosphere waveguide monitoring the electrical conductivity of the waveguide's boundaries. The upper boundary of this waveguide is formed by the lower ionosphere whose electrical properties are represented by Wait's parameters (Wait & Spies, 1964), namely, reference height (H_0) and conductivity gradient (β). During daytime, the solar Lyman α (Ly α) radiation is the main source of ionization of the quiescent lower ionosphere (Nicolet & Aikin, 1960). However, this quiescent ionospheric condition is disturbed by increases or decreases of ionization caused by solar and nonsolar-terrestrial events, such as solar flares, solar eclipses, gamma ray bursts, and particle precipitation (Bracewell et al., 1949; Bracewell, 1952; Fishmann & Inan, 1988; Helliwell et al., 1973). Any disturbance in the lower ionosphere producing changes of Wait's parameters shows up as phase and/or amplitude variation in the VLF signal.

While there are different kinds of sources that can produce disturbances in the lower ionosphere, there are many reports about analysis of solar X-ray flare perturbation in the recorded VLF signals (e.g., Bracewell et al., 1949; Muraoka et al., 1977; Pant, 1993; Bouderba et al., 2016). The majority of these studies reported the correlation between the logarithmic of the solar X-ray peak flux (W/m^2) of the flare and the subsequent ionospheric disturbance observed as VLF anomalies. From this correlation it is possible to estimate the smallest solar X-ray flare event that disturbed the daytime lower ionosphere conductivity enough to perturb the propagation of VLF waves (Kaufmann & Paes de Barros, 1969; Khan et al., 2005; Muraoka et al., 1977; Pant, 1993; Raulin et al., 2010). This minimal detected event suggests how sensitive the lower ionosphere is to solar flares; however, more understanding on this notion is needed. Therefore, it is essential to address further the idea of the behavior of the daytime lower ionosphere as a solar X-ray flare sensor using a quantitative parameter that exposes the sensitivity of such sensor.

Some studies have suggested that the ionospheric sensitivity to X-ray events depends on the phase of a solar cycle. Raulin et al. (2006) used records of VLF sudden phase anomalies (SPAs) to study the statistical occurrence of X-ray flares that disturbed the lower ionosphere. They showed that the probability of SPA occurrence produced by faint solar flares is higher during solar minimum and interpreted this probability in terms of ionospheric sensitivity. Pacini and Raulin (2006) used the correlation between the X-ray fluence (time-integrated X-ray emission up to the time of the maximum of the SPA event) of the flare and the phase advance of the produced SPA to determine whether the correlation has a solar cycle phase dependence. From this correlation, they extrapolated the minimum fluence below which no ionospheric response is significant and understood this value as the ionospheric sensitivity. However, their method is used only to estimate the minimum fluence for extreme epochs of a solar cycle. Raulin et al. (2010) used the X-ray peak flux of solar flares in the 0.1–0.8 nm wavelength band and the corresponding size of the SPA to obtain the minimum detected solar event. Combining their results with earlier results of similar studies obtained during different solar cycles, the authors showed that the lower X-ray detection limit varies as a function of the solar activity. However, the use of the X-ray flux in the 0.1–0.8 nm wavelength band may not be adequate to quantify the impact of solar flares in the lower ionosphere. As was shown by Pacini and Raulin (2006) the X-ray emission in the wavelength band less than 0.2 nm is the more efficient to produce ionization enhancements in the lower ionosphere. Furthermore, Pacini and Raulin (2006) showed that the X-ray fluence exhibits the energy of the flare deposited in the lower ionosphere, while the X-ray power is related to the electron production rate.

From previous studies it is clear that different approaches were used to estimate the lowest detectable solar X-ray flare and thus to discuss the ionospheric sensitivity (Pacini & Raulin, 2006; Raulin et al., 2010). Nevertheless, all these studies interpreted that the ionospheric sensitivity is higher during solar minimum than during solar maximum. However, there is a need to have a more complete and homogeneous data set that can serve as a reference for further studies and comparisons. In addition, there is a lack of knowledge on the variability of this sensitivity continuously over a complete solar cycle. Thus, a study of the lower ionospheric sensitivity using the fluence parameter is required to determine its long-term variation over a solar cycle.

The aim of the present study is to infer how the sensitivity of the lower ionosphere varies over a solar cycle by using the ionospheric disturbances produced by solar X-ray flares. With that in mind, the interpretation of ionospheric sensitivity using minimum X-ray fluence, introduced by Pacini and Raulin (2006), was employed. However, in our study the minimum X-ray fluence is obtained by the time integration of the solar X-ray flux from the start time of a flare-up to the beginning of the ionospheric disturbance. This minimum X-ray fluence (F_{Xmin}) is related to the smallest energy deposited and capable of producing the minimum detected disturbance of the quiescent ionospheric conductivity. F_{Xmin} is obtained for all solar flares regardless of their size, which we believe is an improvement of the extrapolation method used in the previous report (Pacini & Raulin, 2006). In this study, the beginning of the ionospheric disturbance is defined as the deviation of the amplitude of the VLF signal from background level. Given the availability of data, we are able to study the variation of the ionospheric sensitivity during the solar cycle 24. In section 2, the data used in this work are presented. The obtained results and their interpretation are presented in sections 3 and 4, respectively. The final section summarizes the conclusions of this study.

2. Data and Methodology

To implement this study, the data collected by two different VLF receiver systems have been used, one located in the polar regions and the other in tropical regions. The use of these two receivers brings the advantage of not restricting the results only to data recorded at high-, low-, or middle-latitude regions. A description of the receiver systems and an explanation of the methodology applied in the corresponding analysis are presented in this section.

2.1. The Ionospheric VLF Data

Data collected by two different types of VLF receivers were used in the analysis. One of them is the Kannuslehto VLF receiver, which is located in northern Finland running under the operation of the Sodankylä Geophysical Observatory (SGO) (Manninen, 2005). This receiver is composed of two square loop antennas and records in wideband, since 2006, all VLF signals between 0.2 and 39 kHz. The antennas, electronics, and acquisition software were all developed and implemented at SGO. Along with Kannuslehto data, data collected by the South American VLF NETwork (SAVNET) receivers were used in this study. SAVNET is a network of VLF receivers composed of one vertical and two square loop antennas installed in different locations in South America and in the Antarctic (Raulin et al., 2009). SAVNET records, since 2006, the phase and the amplitude of VLF radio signals from transmitters located mainly in the U.S., i.e., signals at 19.8 kHz (NWC), 21.4 kHz (NPM), 24.0 kHz (NAA), 24.8 kHz (NLK), 25.2 kHz (NDK), and 40.75 kHz (NAU).

The present analysis uses the amplitude of VLF signals recorded in December and January since December 2007 till January 2016. In this sense, a possible seasonal dependence in the results will be removed. The chosen period of time corresponds to the solar cycle 24. Additionally, we restricted the analysis to north-south oriented VLF propagation paths in order to have similar directions of propagation of the VLF signal recorded at both receivers. In this study, Kannuslehto recordings of the amplitude of VLF signals transmitted by TBB (Turkey, at 26.7 kHz) and the amplitude of the NAA transmitting signal (U.S., at 24 kHz) recorded by the SAVNET receiver located in Brazil (ATI) were our main data set. In addition, when a solar X-ray flare was not observed by those transmitter-receiver systems, the VLF amplitude of HWU (France, at 21.8 kHz) recorded at Kannuslehto and the NAA transmitting signal recorded by the SAVNET receiver in Peru (PLO) were also used.

For the analysis, a selection was made choosing all the amplitude disturbances caused by well-defined time profile solar X-ray flares; i.e., multiple consecutive or superimposed events were avoided. We verified that the selected events occurred during quiet geomagnetic conditions to restrict the analysis for ionospheric perturbation generated by solar X-ray flares. In total, 151 solar X-ray events were catalogued. From these events we removed the events that occurred when the transmitter and/or the receiver were in maintenance, also events for which the VLF signal was not clear enough to define a starting time, or clearly showed the superposition of different flares, and also no detected events. Finally, we ended up with 44 events to be analyzed. It should be stressed that we are interested only in the starting time of the amplitude deviation, independently of its size and shape, since this time evidences that in the lower ionosphere there is enough accumulation of free electrons to perturb the propagation of VLF waves regardless of its frequency.

2.2. The Solar X-ray Data

It was shown by Pacini and Raulin (2006) that during solar flares the photons with wavelength less than 0.2 nm are capable of producing significant ionization enhancement at—and below—the undisturbed reference height of the lower ionosphere (H_0: ~70 km). Thus, to compute F_{Xmin}, the X-ray flux in that wavelength band was first determined. To obtain the solar X-ray flux below 0.2 nm we proceeded similarly as described by Pacini and Raulin (2006). Essentially, preflare-level subtracted X-ray fluxes recorded by both X-ray sensors (0.05–0.4 and 0.1–0.8 nm) of the Geostationary Operational Environmental Satellite (GOES) were used. Additionally, it was assumed that the X-rays were emitted by a hot isothermal plasma associated with the flaring active region.

In contrast to Pacini and Raulin (2006), to represent the characteristics of the solar plasma, we have used the two sets of element abundances of the CHIANTI spectral model: coronal and photospheric (Dere et al., 1997; Landi et al., 2013). This model is based on astrophysical ionized abundant elements from hydrogen through nickel (Dere et al., 1997). CHIANTI version 7.1 (Landi et al., 2013), used in this study, includes a new set of coronal abundances taken from Schmelz et al. (2012) and two new sets of photospheric abundances from Lodders et al. (2009) and Caffau et al. (2011). In principle, for solar X-ray flares the coronal set of abundances is more suitable than the photospheric one because the emitted plasma recorded by GOES resides in coronal loops rather than in chromospheric foot points (Trottet et al., 2011). Nevertheless, we used both sets of abundances for comparison. For each of the set of abundances, the temperature ($T(t)$) and the emission measure (EM(t)) of the flaring plasma were estimated as a function of time (t) using the CHIANTI spectral model (Dere et al., 1997; Landi et al., 2013). At each time t, $T(t)$ and EM(t) were used along with the Mewe thermal spectrum model (Mewe et al., 1985) to obtain the isothermal spectrum of the flare as a function of photon wavelength. Integrating the spectrum below 0.2 nm for each instant t led to the X-ray flux time profile. Eventually, we ended up with two X-ray flux time profiles in the wavelength band below 0.2 nm, one for each set of abundances.

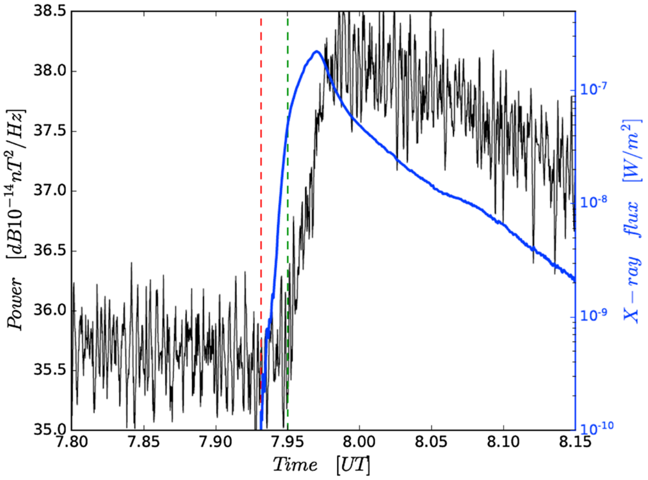

Figure 1. Example of computation of F_{Xmin}. The blue line represents the time evolution of the X-ray flux with wavelength less than 0.2 nm that occurred on 23 December 2013. The black line shows the temporal behavior of the amplitude of the VLF signal transmitted by TBB and recorded at Kannuslehto at the time in which the flare occurred. The vertical red and green dashed lines represent the onset times of the flare and the VLF amplitude deviation, respectively.

2.3. The Calculation of the Minimum X-ray Fluence F_{Xmin}

In the present study, the minimum X-ray fluence (F_{Xmin}) needed to produce a detectable disturbance of the quiescent ionospheric conductivity is computed by integrating over time the solar X-ray flux, with wavelength less than 0.2 nm, from the start of the flare observed by GOES up to the beginning of the associated VLF signal deviation (equation (1)).

$$F_{Xmin} = \int_{t_{XF}}^{t_{VLF}} f(t)dt \qquad (1)$$

where $f(t)$ is the time profile of the X-ray flux and t_{XF} and t_{VLF} are the onset times of the X-ray flare and VLF amplitude deviation, respectively. In this way, the integral computes the minimum X-ray fluence. An example of such procedure is given in Figure 1, where the blue curve shows the flux time evolution of a well-defined X-ray flare, with wavelength less than 0.2 nm, that produced an ionospheric disturbance on 23 December 2013. The black curve shows the amplitude variation of the VLF signal transmitted by TBB and recorded in Finland. The two times t_{XF} and t_{VLF} are represented in Figure 1 by the dashed vertical red and green lines, respectively. t_{VLF} is defined as the time for which the amplitude deviation exceeds 1.5σ, where σ is the RMS of the mean VLF undisturbed amplitude level, i.e., before the solar event, calculated for a time window of 2 min. We applied this method to each of the selected VLF anomalies produced by a solar flare, and the corresponding results are presented in the next section.

3. Results

A list of the events used to compute F_{Xmin} is shown in Table 1. The first column displays the date of the events according to the receiver system used to record the VLF signal variation, SAVNET, and Kannuslehto receivers. The second and third columns of Table 1 show the time at which the X-ray flare in the wave band less than 0.2 nm started (t_{XF}) and the time delay between the start of the flare and the beginning of the VLF signal deviation (Δt), respectively. The last column shows the average value of the amplitude of the VLF signal recorded at the receiver.

The evaluation of F_{Xmin}, computed by the coronal set of abundances, against the peak flux of the X-ray flare in the 0.1–0.8 nm wavelength band is shown in Figure 2. For practical reasons, we have separated the events into two groups. The events that occurred around solar minimum of solar cycle 24 are distinguished as black filled circles and those that occurred around solar maximum are represented with red filled circles. Examination of Figure 2 leads to the following comments: (i) F_{Xmin} values for events occurring during solar minimum are lower than F_{Xmin} values for events occurring during solar maximum. (ii) Regardless of the level of the solar activity, F_{Xmin} does not depend on the X-ray peak flux of the solar flare. Thus, the result in Figure 2 demonstrates a solar cycle dependence of F_{Xmin}. The same result is still valid if we use F_{Xmin} obtained by the photospheric set of abundances, although these last values are between 1 and 2 times greater than those obtained using the coronal set of abundances.

The main result of this paper is shown in Figure 3 as the temporal evolution of the average value of F_{Xmin} computed for every year of analysis since December 2007 until January 2016. In this figure, F_{Xmin} values obtained by the coronal set of abundances are represented by green filled circles, while those obtained by the photospheric set of abundances are represented by orange stars. Here the photospheric values were multiplied by a factor of 0.75 for comparison with the coronal values. In Figure 3, the error bars show 1.3 standard deviations of F_{Xmin} values for every period of analysis. The magenta line shows the time profile of the solar Ly α flux smoothed using the Savitzky-Golay filter with a time window length of 16 months. The smoothed Ly α variation is used as a proxy of the behavior of solar cycle 24. The Ly α data were obtained from the Laboratory for Atmospheric and Space Physics interactive solar irradiance data center (http://lasp.colorado.edu/lisird/lya/) (Rottman et al., 2006; Woods et al., 2000), which provides a composite of Ly α flux based on modeling results and measurements from 1947 to the present time.

Table 1
Date of the Selected Events According to the Receiver System Used

Date	t_{XF} (UT)	Δt (s)	Amplitude ($dB\mu V$)
	SAVNET		
14 December 2007	14.206	133	34.14
01 January 2008	15.555	145	33.58
16 December 2009	12.874	74	27.34
18 December 2009	18.866	45	31.72
02 January 2010	14.192	49	33.98
19 January 2010	17.740	139	31.85
14 December 2011	19.611	136	32.50
26 December 2011	20.231	100	36.19
27 December 2011	12.011	108	32.54
28 December 2011	14.351	92	34.64
28 December 2011	20.277	370	33.78
31 December 2011	16.317	52	37.37
18 January 2012	19.100	78	36.45
25 December 2012	18.112	147	37.95
08 January 2013	19.098	103	34.57
10 January 2013	19.756	167	30.51
12 January 2013	19.432	230	35.14
19 December 2013	15.441	167	33.89
21 December 2013	14.806	165	33.60
28 December 2013	17.910	147	36.31
29 December 2013	14.699	70	35.22
04 January 2014	15.584	147	33.74
11 January 2014	13.015	193	32.47
17 January 2014	13.946	96	33.44
17 January 2014	16.080	126	35.92
28 January 2014	11.612	25	24.08
29 January 2014	11.982	81	29.46
31 January 2014	15.559	137	35.24
17 December 2014	14.965	68	27.22
17 December 2014	18.934	108	27.16
20 December 2014	15.061	68	27.37
20 December 2014	20.505	115	24.48
15 January 2015	14.836	192	26.84
12 December 2015	13.640	64	35.91
27 December 2015	19.020	174	35.94
15 January 2016	15.351	113	36.42
	Kannuslehto		
Date	t_{XF} (UT)	Δt (s)	Power (dB 10^{-14} nT^2/Hz)
14 December 2011	13.327	125	37.03
05 January 2013	9.474	63	45.39
05 December 2013	11.378	162	38.42
21 December 2013	10.481	115	41.97
22 December 2013	14.429	117	63.24
23 December 2013	7.934	64	35.56
11 December 2014	7.934	125	46.09
13 December 2014	10.091	157	44.09

Note. The onset time of the flare (t_{XF}), the time delay between the beginning of the flare and its associated initial deviation in the VLF signal (Δt), and the average level of the VLF recording at the receivers are shown in columns 2, 3, and 4, respectively.

Examination of Figure 3 can be summarized as follows: (i) the values of F_{Xmin} are lower when the solar cycle was at minimum phase and these values increase as the solar activity increases, (ii) the temporal evolution of F_{Xmin} obtained by the coronal set of abundances is quite similar to that obtained by the photospheric set of abundances, and (iii) the variation of F_{Xmin} values follows the temporal evolution of Ly α flux during solar cycle 24 independently of the chosen set of abundances. From Figure 3 and through the coronal set of abundances results we can define a lower limit of F_{Xmin} ~1×10^{-7} J/m^2 below which no ionospheric response can be detected during low solar activity. A similar lower limit for periods of high solar activity is larger and its value is ~7×10^{-7} J/m^2. For the case of the photospheric set of abundances, these limits are ~2×10^{-7} J/m^2 and ~10×10^{-7} J/m^2, respectively.

4. Discussion

In this study the varying sensitivity of the lower ionosphere to solar X-ray flares is inferred using the parameter of the minimum X-ray fluence (F_{Xmin}). F_{Xmin} is a parameter that shows the necessary accumulation of energy to produce a disturbance of the quiescent ionospheric conductivity detectable by the VLF technique; i.e., F_{Xmin} is the photon energy flux integrated over the time interval from the start of a solar X-ray flare to the beginning of its ionospheric disturbance. In the analysis, the X-ray flux in the wavelength band below 0.2 nm, computed assuming a thermal spectrum, was used. The VLF data which were used correspond to the amplitude of the VLF signals emitted by HWU and TBB stations and recorded in Finland, together with the NAA amplitude transmitting signal recorded in Peru and Brazil. In this work we concentrate on the initial time of the VLF amplitude deviation independently of the size of the ionospheric response, because we assumed that the initial deviation in the VLF signal is an evidence of the eventual accumulation of ionization that starts to change the characteristics of the propagation of the VLF signal.

The main result of this study is that F_{Xmin} follows the behavior of solar cycle 24, and particularly the temporal evolution of the solar Ly α flux, with F_{Xmin} values on the order of $(1-12) \times 10^{-7}$ J/m^2. This result suggests that the necessary accumulation of energy that produces a disturbance of the quiescent ionospheric conductivity detectable by the VLF technique is changing over the solar cycle, having lower values during solar minimum than during solar maximum. The long-term variation of this parameter suggests that the ionospheric sensitivity is also changing over the solar cycle, the lower ionosphere being more sensitive when F_{Xmin} has lower values. This means that the long-term variation of F_{Xmin} is anticorrelated with the ionospheric sensitivity. Thus, our study confirms that the sensitivity of the lower ionosphere is anticorrelated to the solar activity cycle. Although this relation was already suggested in the past (Pacini & Raulin, 2006; Raulin et al., 2010), in this paper, the anticorrelation between ionospheric sensitivity and solar activity is deduced continuously using a uniform data set from 2007 to 2016. This period includes both a minimum (2009) and a maximum (2015) of solar activity. Furthermore, we used the X-ray flux in the wavelength band less than 0.2 nm, which as shown by Pacini and Raulin (2006) is the most efficient X-ray radiation to produce ionization enhancements in the lower ionosphere. Other results of our study are that F_{Xmin} does not depend on the X-ray peak flux of the flare and that the temporal evolution of F_{Xmin} obtained by using the CHIANTI model with coronal or photospheric abundances is quite similar.

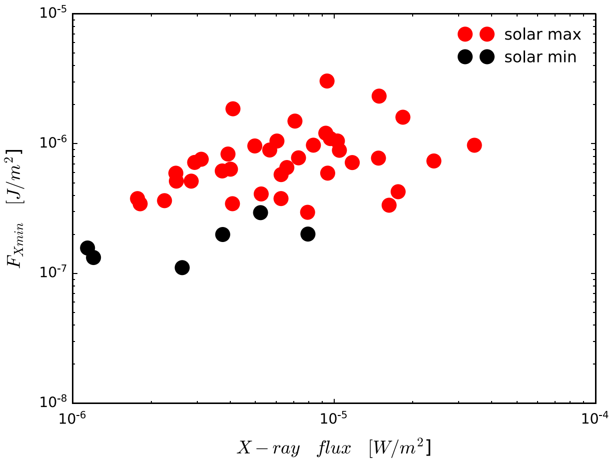

Figure 2. Evaluation of F_{Xmin} obtained by the coronal set of abundances against the peak flux of the X-ray flare in the 0.1–0.8 nm wavelength band. The black filled circles refer to the events that occurred around the minimum epoch of solar cycle 24 and the red ones to the events that occurred around solar maximum.

Since the temporal evolution of F_{Xmin} follows the long-term solar Ly α variation, our results confirm that the undisturbed lower ionosphere is formed and maintained by the solar Ly α radiation, as proposed theoretically by Nicolet and Aikin (1960) and shown observationally by Raulin et al. (2010). Therefore, according to our result, the daytime lower ionosphere starts to respond to solar events with F_{Xmin} values greater than ~1×10^{-7} J/m^2. A more general point of view implies that for a given external source of ionization to produce a measurable disturbance in the lower ionosphere, the corresponding enhancement of ionization would be associated to a F_{Xmin} value greater than the F_{Xmin} values reported in this study, which varies over a solar cycle.

The main result of this study can be interpreted in another way if we recall that at VLF frequencies a variation of the ionospheric sensitivity is related to a variation of Wait's parameters (Wait & Spies, 1964): reference height (H_0) and gradient conductivity (β). In this sense, a variation in any of these parameters will induce a different behavior of the lower ionosphere, which is considered as a sensor of solar X-ray events. Variations of H_0 during extreme epochs of a solar cycle were reported by McRae and Thomson (2000, 2004) and Pacini and Raulin (2006). Similarly, variation in β was reported by McRae and Thomson (2000, 2004). The just mentioned reports describe that H_0 is lower and β is higher during solar maximum as compared with solar minimum. However, it is supposed that H_0 and β are changing continuously along the solar cycle. More specifically, Pacini and Raulin (2006) showed that a larger value of fluence is required to produce a significant disturbance of the ionospheric conductivity when the solar cycle activity increases due to a variation in H_0. Therefore, our result implies that F_{Xmin} can be attributed to changes of Wait's parameters over the solar cycle.

The main result of this paper suggests that F_{Xmin} can also be considered as an ionospheric index capable of reproducing the solar activity cycle variation. Since the daytime undisturbed lower ionosphere is maintained mainly by the direct Ly α radiation, changes of the ionospheric response with respect to the solar cycle imply changes in the Ly α incident flux at the Earth's atmosphere. Therefore, in principle, the daily monitoring of F_{Xmin} could be used as a proxy for the solar Ly α radiation. This is of course not the case at the present time. To do so, the precise monitoring of the VLF reference height of the lower ionosphere would be a better methodology, whose implementation is, however, beyond the scope of this paper. Furthermore, due to atmospheric absorption, Ly α must be measured from space using nowadays sensors installed on satellites. However, our result shows that the study of the impact of Ly α variations on Earth can be indirectly developed by using the properties of VLF wave propagation within the Earth-ionosphere waveguide.

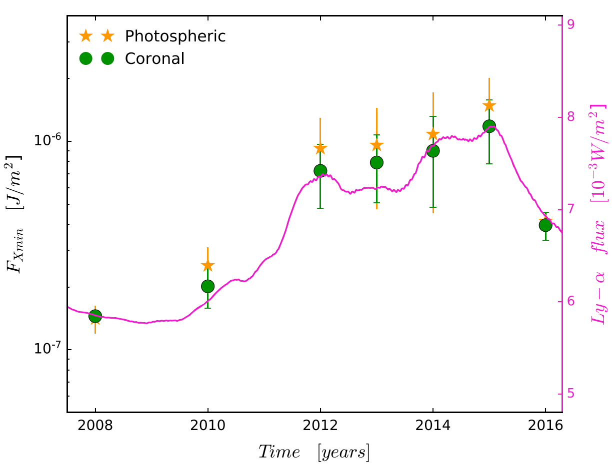

Figure 3. Average values of F_{Xmin}, with their respective error bars, for every year of analysis since December 2007 till January 2016. F_{Xmin} values obtained by the coronal set of abundances are represented by green filled circles and those obtained by the photospheric set of abundances are illustrated by orange stars. The photospheric values were multiplied by a factor of 0.75. The error bars are 1.3 standard deviations of F_{Xmin} values for every period of analysis. The magenta line is the 16 month smoothed time variation of the Ly α flux used as a proxy of solar cycle 24.

It is quite interesting to notice that the amplitude of solar cycle 24 is the smallest sunspot cycle since solar cycle 14. Even so, the long-term variation of F_{Xmin} presented in our study clearly follows the behavior of the solar cycle. Previous reports suggesting a solar cycle dependence of the ionospheric sensitivity were based on data recorded at solar cycles which amplitudes are approximately 2 times greater than solar cycle 24 (Pacini & Raulin, 2006; Raulin et al., 2010). Especially, Pacini and Raulin (2006) using the X-ray fluence in the wavelength band less than 0.2 nm found—by extrapolation—the minimum fluence needed to produce a perturbation in the ionosphere for two extreme cases of solar activity conditions. However, they estimated the minimum fluence using the Mewe/Meyer spectral model (Meyer, 1985). In contrast, F_{Xmin} values found in our study were obtained using the CHIANTI spectral model with coronal and photospheric abundances (Dere et al., 1997; Landi et al., 2013). Comparing the spectral models, we found that the Mewe/Meyer model has higher values than the CHIANTI model. Another difference is that Pacini and Raulin (2006) worked with the phase of the VLF signal and not with the amplitude as we did in our study. In order to compare our result with that of Pacini and Raulin (2006), we performed similar computation shown in Figure 3 using the Mewe/Meyer model. We found that, for solar minimum and solar maximum, the minimum fluences we found using the Mewe/Meyer model were a factor of 15 and 5 lower than the minimum fluences reported by Pacini and Raulin (2006), respectively. However, our result for solar events that occurred around the minimum epoch of solar cycle 24 agrees with the range of minimum fluences reported by Raulin et al. (2014) for the same period of time.

Raulin et al. (2014) addressed the nighttime sensitivity of the VLF response to a series of X-ray bursts emitted by a remote cosmic source that occurred on 22 January 2009. The authors reported that for nighttime conditions the minimum fluence in the X-ray wavelength band less than 0.2 nm is ~2×10^{-9} J/m^2 and that this value is at least 2 orders of magnitude lower than the daytime minimum fluence. Their conclusion is based on the study of 17 simple solar flares producing VLF phase changes using the Mewe/Meyer spectral model (Meyer, 1985), and the authors found that the daytime F_{Xmin} was in the range ~$0.7 - 2.6 \times 10^{-7}$ J/m^2. Therefore, despite the fact that different spectral models were used, and the fact that in our study the ionospheric disturbance is defined as an amplitude (and not a phase) deviation, our result totally agrees with the findings of Raulin et al. (2014).

Additionally, our result is useful to estimate the detectability of any ionizing source (e.g., cosmic bursts and solar flares) in daytime ionospheric conditions over a complete solar cycle; i.e., the minimum fluence of an energetic source of ionization must overcome the F_{Xmin} value introduced in this study in order to cause a measurable disturbance in the daytime lower ionosphere. Finally, the result of this study suggests that using the properties of VLF wave propagation inside the Earth-ionosphere waveguide is a promising technique for a better understanding of the long-term solar-terrestrial relationship. Because the VLF analysis provides information on Wait's parameters, it would be relevant to evaluate the long-term variation of H_0 and β, which will be the focus of our upcoming research.

5. Conclusions

In this paper we have inferred the ionospheric sensitivity of the lower ionosphere by using the minimum X-ray fluence. This parameter was calculated by the integration over time of the solar X-ray flux since the start of the flare to the beginning of the associated VLF signal deviation. In this study, the minimum fluence was computed using the amplitude of the VLF signal recorded during solar cycle 24. We found that the long-term variation of the minimum fluence is correlated to the solar activity cycle, particularly in relation to the temporal evolution of the solar Lyman α flux. We understand our results in terms of the lower ionosphere sensitivity variation. Then, our study confirms indirectly that the sensitivity of the lower ionosphere is anticorrelated with the solar activity level. Our result is important since it suggests that the minimum fluence could be used as a good indicator of the sensitivity of the lower ionosphere. Finally, our result is also important for identification of the minimum fluence that a given external source of ionization (e.g., cosmic burst) must overcome in order to cause a measurable disturbance in the daytime lower ionosphere.

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