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Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 1029–1035

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

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On the detectability of solar X-ray flares using very low frequency sudden phase anomalies

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Received 18 August 2005; received in revised form 25 October 2005; accepted 20 November 2005
Available online 19 January 2006

Abstract

We have studied ionization excesses produced by enhancements of X-ray emission during solar flares using the very low frequency (VLF) response of the lower edge of the ionospheric D region. We focus on whether or not the X-rays associated with a given solar flare were responsible for a sudden phase anomaly (SPA) event, independently of the characteristics of the SPA. Approximately 1300 and 200 solar events were found to cause an ionospheric event, during periods of high and low solar activity, respectively. The main results of the present work are: (i) definite spectral characteristics are required for a solar flare to produce a measurable SPA; (ii) the probability of SPA occurrence due to faint solar flares, of X-ray class C1–C2 or lower, is higher during solar minimum; (iii) the same probability for more intense solar flares (class C3 or higher) does not depend on the solar activity conditions. Our observations suggest that the low ionosphere has different sensitivities depending on the solar activity, being more sensitive when the Sun is less active. These results also constitute an observational confirmation of recent findings showing that the ionospheric reference height is lower (by about $\leqslant 1$ km) during solar maximum.

Keywords: Solar flares; X-rays; Ionosphere; Solar activity cycle; Very low frequency propagation

1. Introduction

The physical processes acting in the D region of the ionosphere are complex and not well understood, both because of the chemistry occurring there and because of the sparse monitoring of this part of the ionosphere. Therefore temporal variations due to transient phenomena like solar flares, and in particular on longer time scales during the solar cycle are still not fully understood. It is common to characterize the ionospheric D region in terms of the parameters, β (conductivity gradient in km^{-1}), and H' (reference height in km), which govern the refractive index of the low ionosphere (Wait and Spies, 1964). During quiet solar conditions, the X-ray emission from the Sun is not a significant

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doi:10.1016/j.jastp.2005.11.004

source of ionization in the D region. However, at the time of explosive events on the solar disk, an excess of X-ray radiation hits the Earth and those photons with $\lambda < 1$ nm can penetrate down to D region altitudes or even lower, and change appreciably the parameters β and H' there.

Sudden Phase Anomalies (SPAs) in very low frequency (VLF) subionospheric propagation are sensitive indicators of the properties of X-ray flux excesses occurring during solar flares. The SPA amplitudes have been found related to the flare X-ray peak fluxes in different energy channels (Kreplin et al., 1962; Kaufmann and Paes de Barros, 1969; Kaufmann et al., 2002; Deshpande, 1972; Muraoka et al., 1977; Pant, 1993; McRae and Thomson, 2004). Particular attention has been given to find out, in a given energy band, what would be the minimum flux (or threshold) F_m able to produce a detectable ionospheric response. The results show that F_m may vary by almost one order of magnitude. As will be discussed later, this may be due to the fact that the ionospheric and solar data bases mixed both maximum and minimum solar activity periods. Although the importance of comparing the threshold power, in a given X-ray energy band, for different solar activity conditions was suggested long time ago (Kaufmann and Paes de Barros, 1969), this has not been reported so far. Only recently, McRae and Thomson (2000, 2004) have studied how the parameters β and H' vary with the solar activity. In the extreme low frequency (ELF) range, Sátori et al. (2005) report several tenths of percent changes of the conductivity height profile across the solar activity cycle.

The goal of the present work is to study the occurrence of SPA events caused by excesses in the X-ray emission associated with solar flares, and to find out how this occurrence varies with the solar activity conditions. In Section 2 we present the data we have used and we show the observational results we have obtained in Section 3. These results are discussed in Section 4 and we present our conclusions in Section 5.

2. Instrumentation and data analysis

We have monitored at Atibaia (São Paulo, Brazil), VLF signals from the Omega navigation network transmitters, in both phase and amplitude. The tracking receivers were controlled by a Cesium beam atomic standard (Piazza and Kaufmann, 1975). In this work we present phase data from North Dakota (NDAK), Haiku (HAI), and Argentina (ARG) transmitters, received at Atibaia (ATI). These data have been complemented by SPA records received at Inubo (INU), Japan (Ionospheric Data in Japan, 1990–1992,1995–1997), from transmitting stations located at La Reunion (LR), Liberia (L), NDAK, HAI, Australia (AUS), and also North West Cape (NWC), Australia which was not part of the Omega network. Details of different paths such as distances and operating frequencies are indicated in Table 1.

The solar flare X-ray measurements were obtained from the GOES full-disk detectors in the energy channels: CH1 (0.1–0.8 nm) and CH2 (0.05–0.4 nm), corresponding to photons of energy between few keV and 15 keV. The peak flux for each flare has been estimated after subtracting a pre-flare X-ray level. A hardening factor, γ, has been estimated by the ratio of X-ray peak fluxes in the CH2 and CH1 channels, i.e. F_{p2}/F_{p1}. We have selected SPA events during which the ionosphere

Table 1
Characteristics of the VLF paths used in this work

Stations	Frequency (kHz)	Distances (Mm)	Period of observation
ATI	(receiver)	–	–
INU	(receiver)	–	–
NDAK	13.1e13.6	from ATI: 9.3 from INU: 9.14	10–12/91 (ATI); 90–92 and 95–97 (INU)
ARG	12.9	from ATI: 2.8	01–03 and 10–12/1991 and 94–97 (ATI)
HAI	11.8e13.6	from ATI: 13.0 from INU: 6.1	94–97 (ATI); 90–92 and 95–97 (INU)
LR	13.6	from INU: 10.97	90–92 and 95–97 (INU)
NWC	22.3	from INU: 6.99	90–91 and 95–97 (INU)
L	13.6	from INU: 14.48	91–92 and 95–97 (INU)
AUS	13.6	from INU: 8.27	92 and 95–97 (INU)

The first three columns indicate the station identification, the operating frequency (kHz) and the distances (Mm) to the receivers. In the last column we indicate the time periods of the observations.

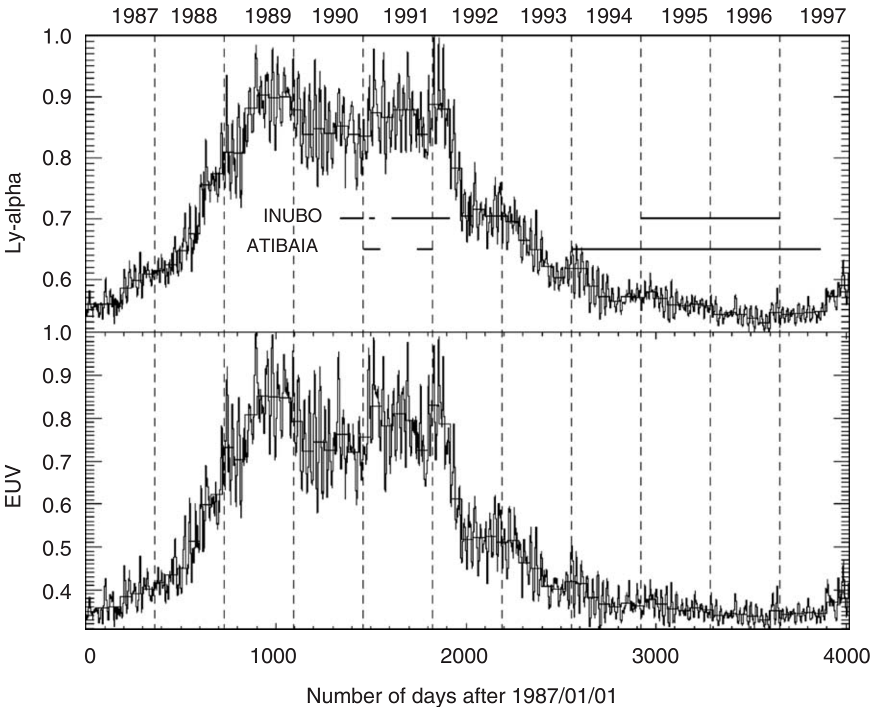

Fig. 1. Horizontal full thick lines illustrate the observing periods of the data used. These lines are superimposed on the time evolution of two solar proxies.

above the detecting path was totally illuminated, or sunlit.

In Fig. 1 we show the time coverage of the data, using horizontal lines, comparing with 11 years of two proxy solar indices which are parts of the SOLAR2000 Research Grade model (Tobiska, 2004): EUV wavelength and the line Ly-α emission normalized to their respective maxima. These wavelengths are believed mainly responsible for the formation of the quiet day ionosphere. Since these radiations are not measured continuously, the proxies are reconstructed from observations and models to ensure long time series, for example using data from Atmospheric Explorer-E (AE-E), the Solar Mesospheric Explorer (SME), and the Upper Atmosphere Research Satellite (UARS) for the Lyman-α irradiance (Woods et al., 2000). Therefore Fig. 1 shows that we have explored time periods of different solar activity characteristics.

3. Observational results on the detectability of sudden phase anomalies

In this section we describe our observational results. We stress out that we are interested only in the X-ray peak flux of those solar flares that produced a SPA, independently of the size of the ionospheric response and of the solar zenith angle χ. The relation between the SPAs intensities and the solar X-ray fluxes (e.g. Kaufmann and Paes de Barros, 1969), as well as the study of those solar flares that did not produce SPAs (Kaufmann et al., 2002), are beyond the scope of this paper. Even if we did not take into account the solar zenith angle χ, we mention that the following results are similar if we choose only the SPA-producing X-ray flares with χ lower than 30°.

In Fig. 2 we show scatter diagrams for all the solar flares detected in X-rays that have been associated in time with SPAs. For each flare, F_{p1} and F_{p2} are shown as a function of γ and for different solar activity time periods (quiet: left column; active: right column). The horizontal dashed lines serve as a reference level, and allow us to see that during low solar activity time periods more than 15% of the total number of X-ray-flares-producing SPAs are such that $F_{p1} < 10^{-6}\,\mathrm{W\,m^{-2}}$ in channel CH1. A similar statement is also true for channel CH2 for which we have $F_{p2} < 10^{-7}\,\mathrm{W\,m^{-2}}$. These percentages reduce to less than a few percents during solar maximum epochs (right column). Moreover we note that the minimum X-ray flux

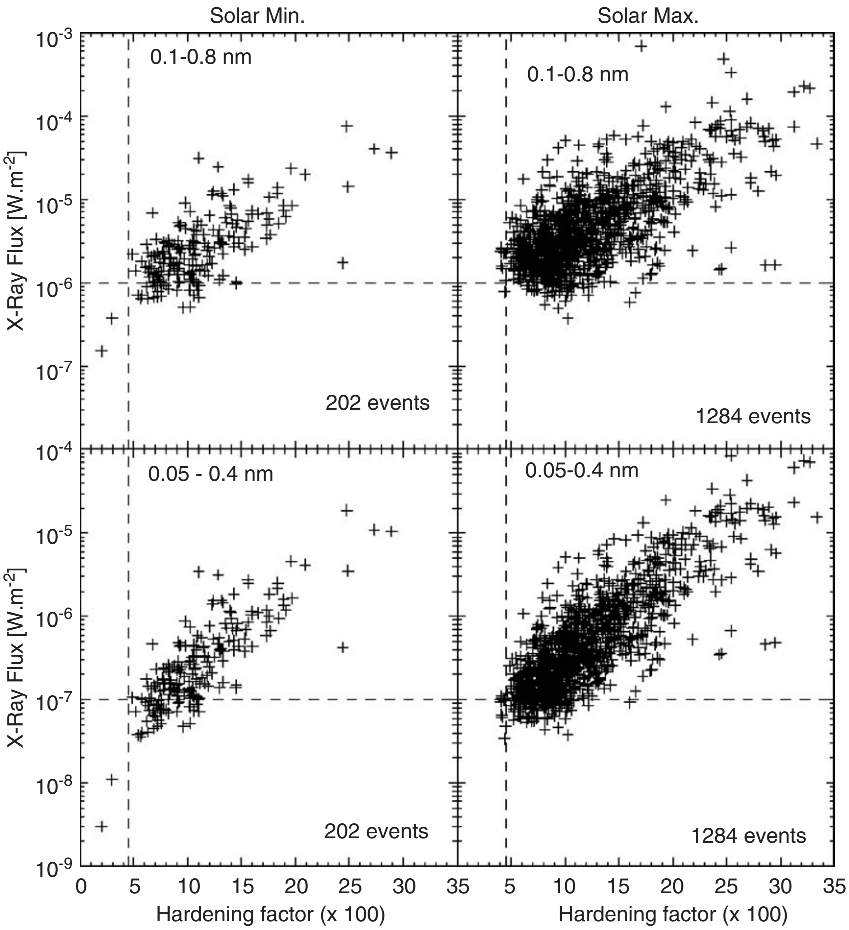

Fig. 2. Background subtracted GOES X-ray peak fluxes in channels CH1 (top) and CH2 (bottom) versus hardening factor γ for all the solar flares that have produced a SPA during solar minimum (left) and maximum (right) time periods. Horizontal dashed lines are just indicative of a certain X-ray power level (discussed in the text).

that produced a SPA is slightly lower during solar minimum conditions than during solar maximum. Finally, Fig. 2 shows (see the dashed vertical lines) that the vast majority of X-ray flares producing SPAs have a hardening factor greater or equal to 0.045, irrespective of the time of the solar cycle.

In order to strengthen the above results we have made plots of the distributions of F_{p1} and F_{p2} values. These are shown in Fig. 3 where the vertical axes are the proportion of solar flares producing SPAs, with a peak flux within a given range. Therefore, the distribution shown has to be understood as the probability, P, for a given X-ray class flare to produce a SPA. We see a quite distinct behavior for solar flares depending on their peak flux F_{p1} and F_{p2} values. For those flares with $F_{p1} \geqslant 2$–$3 \times 10^{-6}\,\mathrm{W\,m^{-2}}$ (top) or $F_{p2} \geqslant 2 \times 10^{-7}\,\mathrm{W\,m^{-2}}$ (bottom), the probability P is roughly independent of the level of solar activity during which the solar event occurred. On the other hand, for solar events with $F_{p1} \leqslant 2 \times 10^{-6}\,\mathrm{W\,m^{-2}}$ (top) or $F_{p2} \leqslant 2 \times 10^{-7}\,\mathrm{W\,m^{-2}}$ (bottom), their probability of producing SPAs is greater during solar minimum compared to that during solar maximum. We note that the bin size of the histogram is $0.3\,\mathrm{W\,m^{-2}}$ and we note that its value does not modify the shape of the distribution, at least for X-ray events up to GOES-class M, i.e. with a peak flux $10^{-5}\,\mathrm{W\,m^{-2}}$.

In Fig. 4 we have plotted the cumulative distribution corresponding to Fig. 3, i.e. its integral as a function of the X-ray peak flux. To get an idea of the order of magnitude of the lower limit of X-ray flux (F_m) needed to produce a SPA, we show a horizontal line at a flux level below which less than 15% of the total solar events have been detected. This means that the probability of occurrence of a

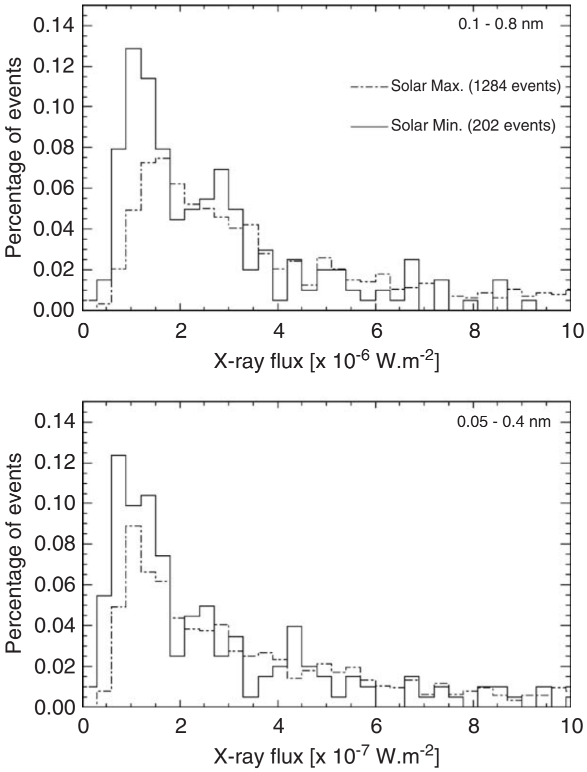

Fig. 3. Occurrence distribution of F_{p1} (top) and F_{p2} (bottom) values for solar events during solar minimum (full line) and solar maximum (dashed line).

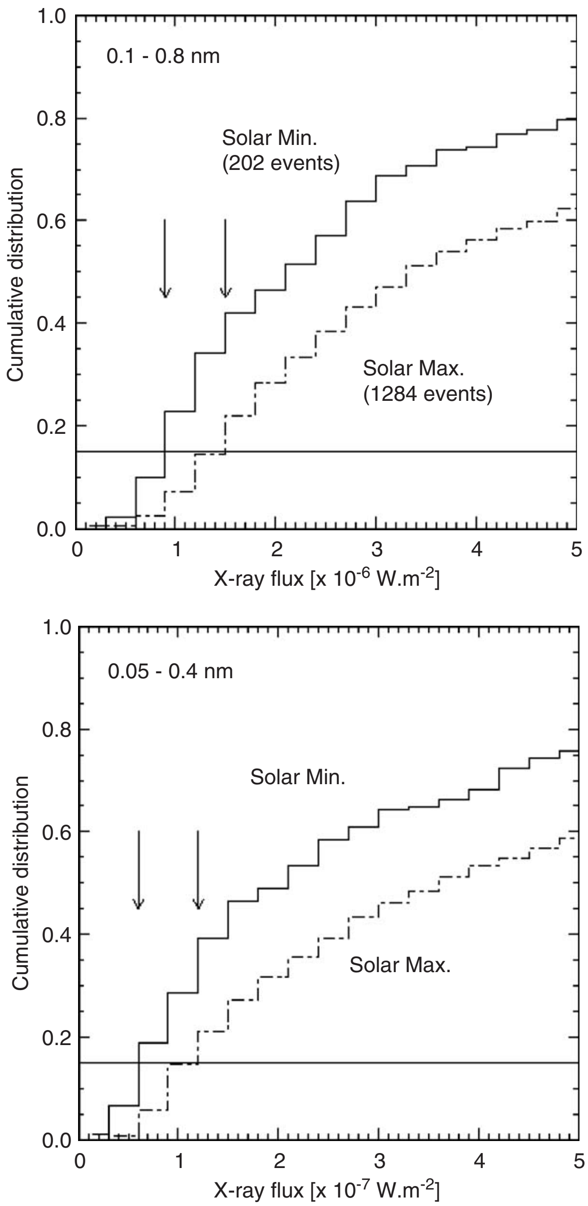

Fig. 4. Cumulative distribution of F_{p1} and F_{p2} values showing, for a given X-ray power F, the probability occurrence of a SPA caused by a solar flare with a X-ray peak flux lower or equals to F.

SPA caused by a solar flare with peak flux lower than F_m is 0.15. The corresponding levels are therefore $0.9 \times 10^{-6}\,\mathrm{W\,m^{-2}}$ and $1.5 \times 10^{-6}\,\mathrm{W\,m^{-2}}$ for solar minimum and maximum periods, respectively for the CH1 channel. These values are referred to B9 and C1.5 X-ray GOES-class solar events, respectively. For the channel CH2 we find similarly 6×10^{-8} and $1.2 \times 10^{-7}\,\mathrm{W\,m^{-2}}$ for solar minimum and maximum periods, respectively.

4. Discussion

We have analyzed the detectability of solar X-ray flares using records of VLF sudden phase anomalies. Approximately 1300 and 200 solar events, respectively, were selected for their ionospheric responses during solar maximum and solar minimum. In this work we concentrate on the size of the solar events that produced SPAs independently of the intensity of the ionospheric response as well as of the solar zenith angle. The main results of the present work are: (i) almost all the solar flares responsible for a measurable SPA have a hardening factor greater than 0.045; (ii) the probability of SPA occurrence due to solar flares of X-ray class C1–C2 or lower, is higher during solar minimum compared to solar maximum; (iii) the probability of SPA occurrence due to more intense solar flares (class C3 or higher) does not depend on the solar activity time period; (iv) the X-ray flux value, F_m, for which the probability of SPA occurrence is less than 15% is lower during solar minimum compared to during solar maximum.

The search for the minimum solar X-ray flux, F_{min} that could produce an ionospheric SPA has been reported many times in the past (Kaufmann and Paes de Barros, 1969; Kaufmann et al., 2002; Muraoka et al., 1977; Pant, 1993; McRae and Thomson, 2004), using various X-ray energy bands from 0–0.3 nm for the most energetic to 0.8–2 nm. In most of these works the way to find out F_{min} was to correlate the SPA amplitudes to the logarithm of the X-ray peak flux. However the results generally disagree between each other, sometimes by almost one order of magnitude. For example in the channel 0.1–0.8 nm, Kaufmann et al. (2002) found $F_{min} = 5.0 \times 10^{-6}\,W\,m^{-2}$ while Fig. 2 of McRae and Thomson (2004) shows $F_{min} = 10^{-6}\,W\,m^{-2}$. Many reasons may have caused these discrepancies such as different SPA normalizations, in particular for the angle χ (Chilton et al., 1963), or the use of the solar event X-ray peak flux instead of the pre-flare background subtracted peak value. The latter is critical and especially for small solar flares which may have their peak flux reduced by a factor 3 or more after the pre-flare background is subtracted. Another alternative is that the cited works did not discriminate the studied events depending on the solar activity period when they occurred. In general, the time periods analyzed involved epochs of both solar minimum and maximum. In the present work we have carefully separated the data and compared the observational results obtained during quiet solar activity to those obtained during high solar activity. Under these conditions we have shown that the occurrence of SPA in the low D region does depend on the solar cycle conditions.

We can understand our results if we assume that the low ionospheric D region has a different sensitivity for different solar activity cycle periods. At VLF frequency ranges SPAs originate because of a change in the reference height H', consequently a change in the reflection height, rather than a change in the refraction index along the wave propagation path (Mitra, 1974). Then the different behavior of the low ionosphere response to small C class solar events during solar maximum and minimum, can be interpreted as different reference heights, i.e. reflection heights. Recently, McRae and Thomson (2000, 2004) have used the long wave propagation capability (LWPC) code to interpret VLF phase and amplitude daytime variations observed on long paths. Their work effectively shows that the ionospheric height is somewhat lower (by about $\leqslant 1$ km) during solar maximum as compared with solar minimum. It is interesting to note that although the above height change is rather small (about 1% of the average reference height for normal day conditions), it produces clear differences in the SPA occurrence probabilities as shown in Fig. 3. We believe that these differences only show up after the careful treatment on the ionospheric and the solar data, in particular the epoch when the events happened and the removal of the pre-flare X-ray emissions. The lack of such treatment probably can explain the discrepancies in previous works as mentioned earlier. Finally we mention that, although a change of the reflection height can explain our results, the effect of the variations of the sharpness parameter β with the solar activity cycle (McRae and Thomson, 2000) has not been taken into account. However this change in β during the solar cycle is unlikely to be a very significant factor here.

5. Conclusions

In this work, we analyzed the detectability of solar flares in the low ionospheric D region using Sudden Phase Anomalies (SPAs) detected at VLF and produced by the excess of X-ray emission characteristics during the solar events. For this, we carefully separated the events depending on whether they occurred during solar maximum or minimum periods, and we removed the pre-flare X-ray signal in order to estimate the peak fluxes. Our main result is that the probability of detecting SPAs produced by low X-ray C class (GOES) flares is higher at the time of minimum of solar activity. For larger X-ray class (GOES) flares, this probability is solar-cycle independent. This finding can be understood if the low ionosphere D region is more sensitive during low solar activity epochs. The results obtained also nicely agree with the findings of McRae and Thomson (2000, 2004) which show that the ionospheric reference height is higher during solar minimum time periods.

Acknowledgements

We thank two anonymous referees for a detailed reading of the text and useful comments. JPR and PK would like to thank Brazilian funding agencies CNPq (Procs: 304433/2004-7 and 300249/2003-4) and FAPESP (Proc. 2005/51422-6) for their support.

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