Ionospheric response caused by solar flares.

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Abstract

We use the new SAVNET network to study 118 SPA events produced by solar flares that occurred between April 2007 and February 2011, corresponding to the minimum 23rd solar cycle and beginning of 24th solar cycle. For this period we detected events with intensities greater than GOES B6 class with a probability of 100%. Comparing the SPA's normalized amplitudes, Φ, with the X-ray solar flux peak excess, the fluence (time-integrated photon fluxes) in the 0.5 – 2.0 Å band, F_x, and the ionospheric production peak we see that lower ionosphere has an exponential response with the solar flares. This behavior can be related with time delay for slower faints X-ray events and loss process during the evolution of the SPA.

Introduction

The investigation of the low ionosphere behavior can be achieved by analyzing the characteristic of VLF (Very Low Frequencies, 3 – 30 kHz) waves propagating over long distances inside the Earth – Ionosphere waveguide. The phase and amplitude variation of the VLF signals give information about electrical properties of the waveguide's boundaries.

The main ionization source of the undisturbed daytime ionospheric D region is the solar Lyman-α radiation (Nicolet and Aikin, 1960). But during solar flares significant ionization enhancements occur, leading to the increase on the D-region density that causes changes in the electrical conductivity at the upper waveguide edge along the trace of the VLF signal.

Pacini and Raulin, 2006 showed that solar photons with $\lambda \leq 2$ Å can reach altitudes below the upper boundary of the waveguide earth-ionosphere, producing an effect of lowering of this edge, that is observed as Sudden Phase Anomalies (SPA). The SPAs are sensitivity indicators to study the X-ray flux excess during solar flares (Kaufmann and Paes de Barros, 1969; Muraoka et al., 1977, Pant, 1993, Mc Rae and Thompson, 2004, Raulin et al, 2006, Zigman et al., 2007). In this work we study the relation between the intensity of the solar X-ray flares and sudden phase anomaly amplitudes detected by a new VLF instrumental facility, the South America VLF Network, SAVNET (Raulin et al. 2009a, Raulin et al., 2009b).

Instrumentation and data selection.

SAVNET is an international project between Brazil, Peru and Argentina dedicated to monitor the effects of the solar activity in the lower ionosphere and in particular over the South Atlantic Magnetic Anomaly (SAMA) region. In Figure 1 we show the location of the SAVNET receiver bases as well the positions of VLF transmitters and the propagations paths from NAA and NPM to Piura (PIU), Punta Lobos (PLO) and Casleo (CAS).

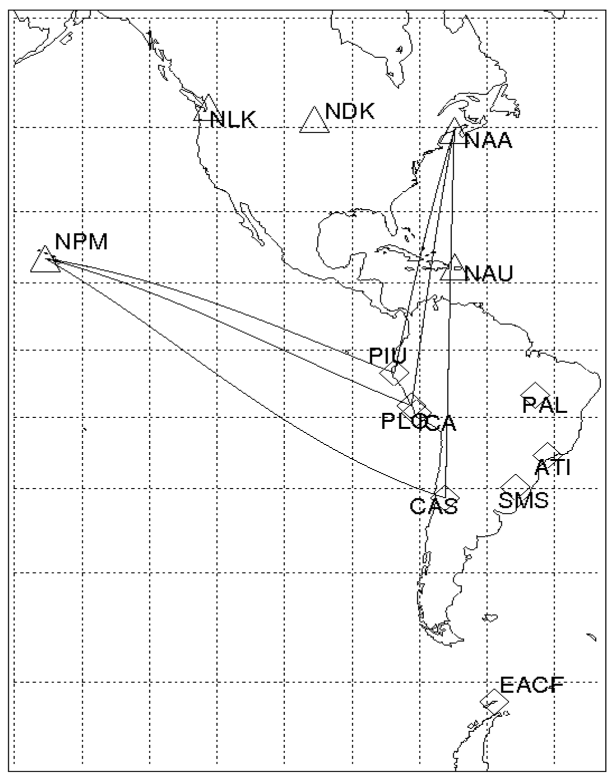

Fig.1 - The receiver bases of the SAVNET array (Δ), transmitters (◊) and VLF propagation paths.

The solar database used in this work is composed of solar X-ray fluxes from GOES detectors which record the solar radiation in two photon energy channels, 1 – 8 and 0.5 – 4 Å. For this data collection we have chosen the simplest events, i.e., those that with a simple time profile. By this criterion, a total of 118 events were selected from

April 2007 to February 2011. This period cover the minimum 23rd solar cycle and beginning of 24th solar cycle.

X-Ray Data Analysis.

The intensity of X-ray events is the excess of emission above the background at each channel. From the ratio between the X-ray fluxes detected in the two energy channels, after subtracting the background, we determined the temperature time profile of the emitting plasma assuming Mewe isothermal spectral models (Garcia, 1994). Due the lower ionosphere is affected by photons with $\lambda \leq 2$ Å (Pacini 2006, Pacini and Raulin, 2006), we computed the X-ray emission time profile integrated in the 0.5 – 2 Å energy band. Finally, we integrate in time the X-ray profiles between the starting time of the X-ray emission and the time of the maximum of the corresponding SPA event, obtaining in that way, for each solar flare, its X-ray fluence, F_x, in J m^{-2} (Pacini, 2006, Pacini and Raulin, 2006), which gives an estimation of the energy amount injected in the lower ionosphere.

Results

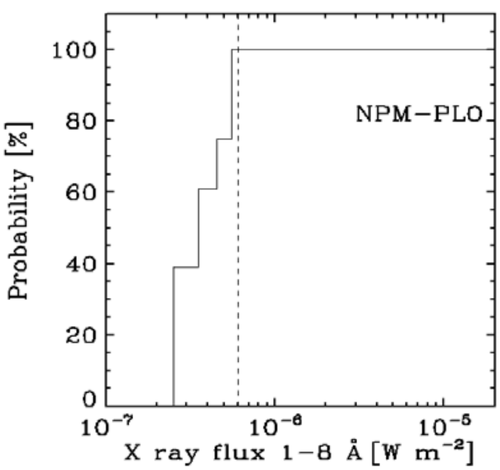

Fig. 2 – Solar flare probability detection for the NPM-PLO VLF propagation path for solar zenith angle lower than 70º.

The capability of detecting solar flare events from SPA effect is shown in the Figure 2, whose criterion of SPA's detection is have SPA greater than 1.5 σ (RMS) compared to the mean preflare VLF phase. This histogram shows the probability for detecting solar flares at $\chi < 70°$, and the dashed bar indicated the value of X-ray flux intensity for which the probability of detection is 100%. The results indicate that solar flares with a X-ray flux peak ≥ 6 x 10^{-7} W m^{-2} (GOES B6 class) will be detected with a probability of 100% in the low ionosphere. Events greater than 3 x 10^{-7} W m^{-2} (GOES B3 class) has a probability of 39% to be detected. This result is above the one obtained by Raulin et al., 2010, because the Lyman-α solar radiation began to increase from 2010, lowering our sensibility of detection.

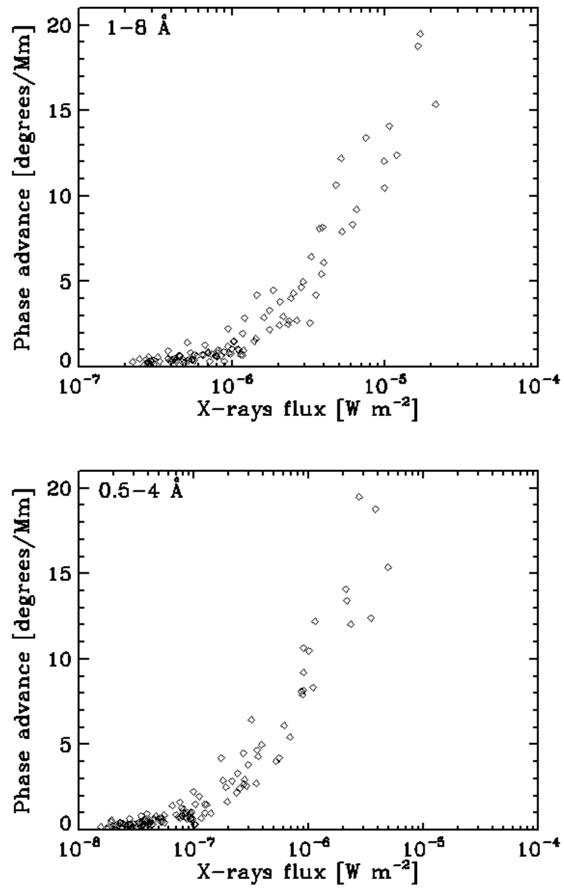

Fig. 3 - Correlation between Φ (degrees/Mm) and GOES soft X-ray peak fluxes in the 1-8 Å and 0.5 – 4 Å excess.

Figure 3 shows the correlation between the SPA amplitude normalized by the illuminated path in the instant of maximum of solar flare, Φ, (in degrees/Mm) and GOES soft X-ray peak fluxes excess (in W m^{-2}) for both energy channels. The minimal response for 1 – 8 Å and 0.5 – 4 Å channels is 1.90 x 10^{-7} W m^{-2} and 1.55 x 10^{-8} W m^{-2} respectively. Both plots show that the lower ionosphere responds exponentially to the intensitiy of X-ray solar flares. This exponential behavior was also reported previously by Ohshio, (1969), analyzing 35 events between March 1966 to April 1966 for 0.5 – 5 Å band.

Pacini (2006) showed that the fluence calculated in the 0.5 – 2 Å band has a better relation with the SPA. The comparison between the SPA normalized amplitude, Φ (in degrees/mm), and fluence, F_x (in J m^{-2}) for this band, is in the Figure 4, which also shows an exponential behavior. For our results the minimal value of fluence for producing an ionospheric response is 6 x10^{-8} J m^{-2}.

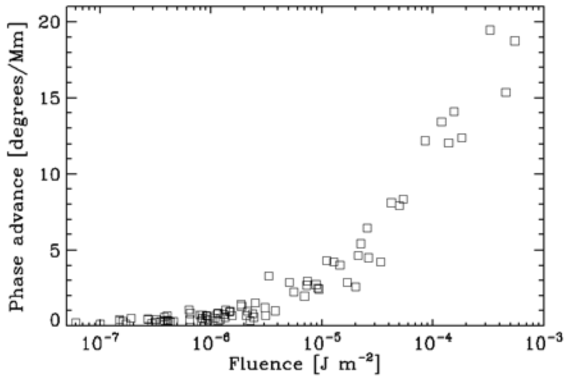

Fig. 4 - Relation between SPA amplitudes and x-ray fluence of the ray emission in the 0.5 – 2 Å.

We estimated the ionospheric production profiles (e ions cm^{-1} s^{-1}) in the 0.5 – 2.0 Å band using the local photoionization efficiency curves of Ohshio (1979). The relation between the intensity of solar flares in the 0.5 – 4.0 Å channel and the SPA for several zenithal angles can be seen in the Figure 5. In the panel (a) we can observed that relation between the ionospheric production and the X-ray flux peak is linear, however we obtain an exponential curve when compare with the SPA's intensity, as noted in the panel (b), specialty for production's peak with χ less than 60°. This plot shows that the production process hasn't produce the exponential relations that observed in previous plots, implicating that probably the loss process that appear during the formation of SPA have a role in this.

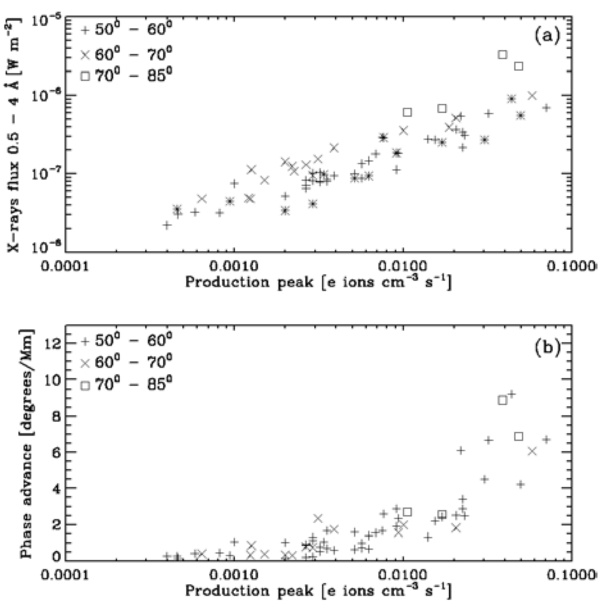

Fig. 5 – Correlations between the peak of production profile with the peak solar flux in the 0.5 – 4.0 Å (superior panel) and the SPA normalized (inferior panel).

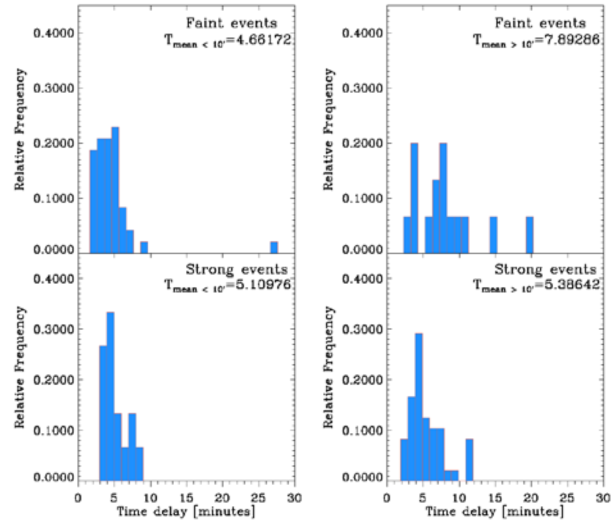

Fig. 6 – Time delay between SPA and X-rays fluxes peaks for faint and strong events.

Finally, we analyzed the time delay between the SPA's peak and the maximum of the solar flare for 0.5 – 4 Å channel, Δt. We grouped the time delay data set for faint (lower than GOES C1.5 class) and strong (greater than GOES C1.5 class) events, whose histograms are shown in the Figure 6. In the left panel are showed both group of events for faster events (time growth of X-ray solar flux ≤ 10 minutes), and in the right panel we have slower events (time growth of X-ray solar flux > 10 minutes). Each plot have its respective mean time delay. We can see that only faints slower events have a higher dispersion, compared with to the others histograms.

Conclusions

Our results confirm the high sensitivity of the lower ionosphere to detect weak X-ray solar events in periods of minimum solar activity. During the period of study the response of lower ionosphere was exponential, probable consequence of the loss process and a high time delay of Δt for slower weak X-ray events. These effects can be better understand when analyze the effects of loss process, calculating the effective recombination coefficient for each event and obtain the electronic concentration profile.

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