# A study of solar flare electromagnetic effects on the ionosphere of southern Brazil during solar cycle 23.

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## Abstract

The solar x-ray radiation follows a behavior similar to the solar cycle activity, which results in periodic disturbances on the Earth's atmosphere. Among the most intense solar activity events are the solar flares: sudden, localized, transient increases in brightness caused by active regions near sunspots. The data analysis for investigation of this phenomenon can provide important information about the Sun/Earth interaction, Magnetospheric effects, as well as events occurring in the Ionosphere which may lead to disturbances in telecommunications, small satellites or even in the Space Weather. In this work we study the characteristics of high-intensity flares (X class) and its effects on the Earth occurred during the solar cycle 23 (1996 - 2007). For this purpose, we utilize X-rays data (in the range 0.5 to 8 Å) from the GOES satellites (Geostationary Operational Environmental Satellites), as well as the equipments dedicated to study the Solar-Earth interactions at the Southern Space Observatory (SSO/CRS/INPE – MCT), (29°S, 53°W), São Martinho da Serra, RS, Brazil, such as riometer and magnetometer. With these tools, we search for any correlation between the solar activity and the ionospheric phenomenon, such as the Sudden Ionospheric Disturbance (SID), and magnetic crochet. These disturbances may cause sudden changes in the ionospheric density and variations in the components of the geomagnetic field that allow us to infer about the disturbed currents in the ionosphere.

## Introduction

The simplified physical mechanism of a solar flare can be described in three phases: initial, explosive, and decay (hot) phases. Each phase has its own dominant mechanism: the turbulent heating of the current sheet is related to the initial phase; the generation of accelerated particles through the fracture or fractures of the current sheet is the remarkable mechanism of the explosive phase, while the decay phase is marked by the cooling of the hot region (Somov et al., 1972). The enhancement of X-ray and ultraviolet radiation intensities that is observed during chromospheric flares on the Sun causes a sudden intensification in the production of free electrons increasing the electron density in the ionosphere layers (Afraimovich, 2001). These density variations are different for different altitudes and are collectively called Sudden Ionospheric Disturbances (SID). SID observations provide a key means for ground-based detection of solar flares along with optical observations of flares and solar radio burst observations (Mitra, 1974). The current study presents and discusses some outstanding events which occurred in the solar cycle 23: a large solar flare (X14.4) on 15 April 2001, the biggest recorded flare (X28+) on 4 November 2003, and the lasts X-class solar flares, on 5 (X9.0) and 6 (X6.5) December 2006 and their sudden ionospheric disturbance measured with riometer and magnetometer. The riometer is used to investigate the cosmic noise (38.2 MHz) and the fluctuations in the ionospheric absorption (Stauning, 1996). The magnetometers data were important to study the induced currents in the ionosphere that may change the components of the geomagnetic field observed on the ground (Rastogi, 1965). These solar flare effects (SFE) are due to a pure ionization enhancement without any change of the electric field. This transient event of solar disturbance can be a good diagnostic for studying the direction of ionospheric current vector and for understanding the important solar terrestrial relationship (Rastogi, 2003). The main purpose of this work is to present the study of high-intensity solar flares characteristics and its effects on the Earth atmosphere/Ionosphere via data of riometer and magnetometer positioned in the Southern Space Observatory.

## Data sets and Methodology

To analyze the solar variation and the occurrence of solar flares, we use data series from Geostationary Operational Environmental Satellites (GOES). These satellites have an instrument X-ray Sensor (XRS) which monitors the radiation in X-rays in ranges 0.5-4.0 Å and 1.0-8.0 Å (Aschwanden, 1994). These data series can be obtained through the database of the National Oceanic and Atmospheric Administration (NOAA). Using this data it was possible to identify 1442 M-Class flares and 112 X-Class flares in the period from 1996 through 2007, the duration of the solar cycle n° 23. With the X-ray data we selected four large flares events occurred at local daytime on the solar cycle 23: a large solar flare X14.4 on 15 April 2001 measured by GOES at 13:50 UT, the largest in the

NOAA records X28 (Tsurutani, 2005) class flare at 19:50 UT on 4 November 2003 and the lasts X-class flares on 5 and 6 December 2006, the peak fluxes at Earth occurred at 10:35 UT and 18:47 UT, respectively. After that, we analyze its X-ray curve characteristics, such as the intensity of the flares and the duration of the phases. In order to verify the effects of solar flares in the terrestrial Ionosphere, we used the data of the riometer and magnetometer dedicated to the study the Solar-Earth relationship at Southern Space Observatory. The riometer utilized in this study consists of 4x4 antenna array (dipole units) used to investigate the cosmic noise (38.2 MHz) and the variation of the ionospheric absorption (Stauning, 1996). We selected 3 riometer's antennas and the X-ray flux data between 1 and 8 Å observed by the geostationary satellite GOES-12. With these data we intend correlate the solar flare and the sudden ionospheric changes, as the density increase in the D and E ionospheric layer analyzing the start and end times, as well as the amplitude. The magnetometers data (magnetograms) were used to study the induced currents in the Ionosphere and to identify the Magnetic Crochet or solar flare effects that cause sudden changes in the components of the geomagnetic field components (H, D, Z). The data are also used to investigate the proportional progression of the X-ray and the ionospheric current. The local time (L.T.) of SSO is taken by UT - 3 h.

### Results

Observations of solar X-ray data in the spectral range of 1 and 8 Å (long sun channel) from GOES-12 during the solar cycle 23 (1996-2007) are analyzed to identify some of the most intense solar X-ray flares occurred at local daytime. The Solar X-ray flux data for this proposed period are represented in the Fig. 1. Thus, with these requirements, the most appropriated flares to this study are the X14.4 on 15/04/01, X28 on 04/11/03, X9 on 05/12/06 and X6.5 on 06/12/06. These selected events are indicated in the Fig.1. The X-ray intensity and time proportion during the four selected flares are presented in the Fig. 2. Identifications and analysis of the solar flare effects on the terrestrial ionosphere/atmosphere is based on the data of the SSO riometer and magnetometer. With the riometer data we analyze the lasts flares on 5 (X9.0) and 6 (X6.5) December 2003. The GOES soft X-ray observations in Fig. 2 shows that the X9 flare started at 10:18 UT reaching its maximum was at 10:45 UT and the X6.5 flare started at 18:29 UT with its peak at 19:00 UT. The X-ray flux data observed by GOES-12, on 5 and 6 Dec 2006, and three riometer antennas are showed in the Fig. 3a.b, respectively The phenomena identified probably are the Sudden Cosmic Noise Absorption (SCNA), a kind of Sudden Ionospheric Disturbance (SID) which has an impulsive increase in the density of ionized matter (plasma) in the ionosphere (Davies, 1969). The SIDs occurrences are demonstrated in the antennas N4E3 of the Fig. 3a.b. The SID occurrence is meanly due to a solar ultraviolet and soft X-ray radiation that generates enhancements of the D and lower E-region ionization over the entire solar illuminated part of the Earth (Hargreaves, 1992).

The electron density increases may cause corresponding increases in the ionospheric absorption of radio waves. Such absorption events may last for the duration of the flare events, i.e. from a fraction of a minute to several tens of minutes (Ranta *et al.,* 1993). However, it is difficult to obtain clear-cut results for the magnitudes of SID since the solar radio bursts are superimposed on the ionospheric absorption produced in association with the emission of X-rays, during the explosive phase of solar flare, in accordance with Sakurai, 1996.

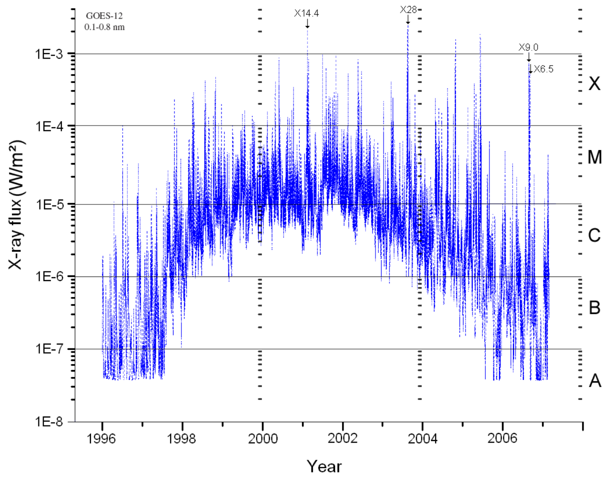


**Fig. 1** – Variation of X-ray flux between 1 and 8 Å by GOES-12 data for the solar cycle 23 (1996 - 2007). The four solar flares events analyzed in this work are indicated.

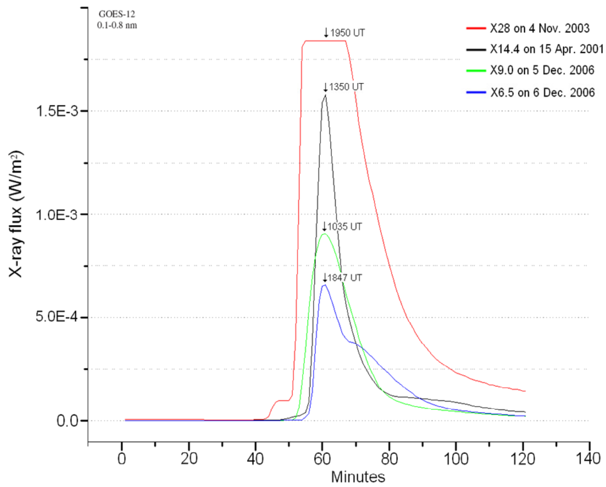


**Fig. 2** - Comparative graphs of the X-ray flux by GOES-12 during the four analyzed flares in this work. The Halloween event (X28 by NOAA) presents saturated in $17.8x10^{-3}$ $W/m^2$ data.

These radio bursts are observed by the antennas N1E2 and N4E2 showed in the Fig. 3a and by the antennas N1E2 and N2E2 in the Fig. 3b. Therefore, it is very difficult to estimate the maximum decrease of cosmic noise intensity, due to the ionospheric absorption, because the emission of solar radio bursts, which normally starts before the maximum decrease, is obtained in the riometer data. The magnetometer data (magnetograms) are use to analyze the X-class flares occurred on 15 April 2001 (X14.4) and 4 Nov. 2006 (X28). The GOES soft X-ray observations in Fig. 2 shows that the X14.4 flare started at 13:19 UT and its maximum was at 13:55 UT and the X28 flare started at 19:29 UT with peak at 20:06 UT.

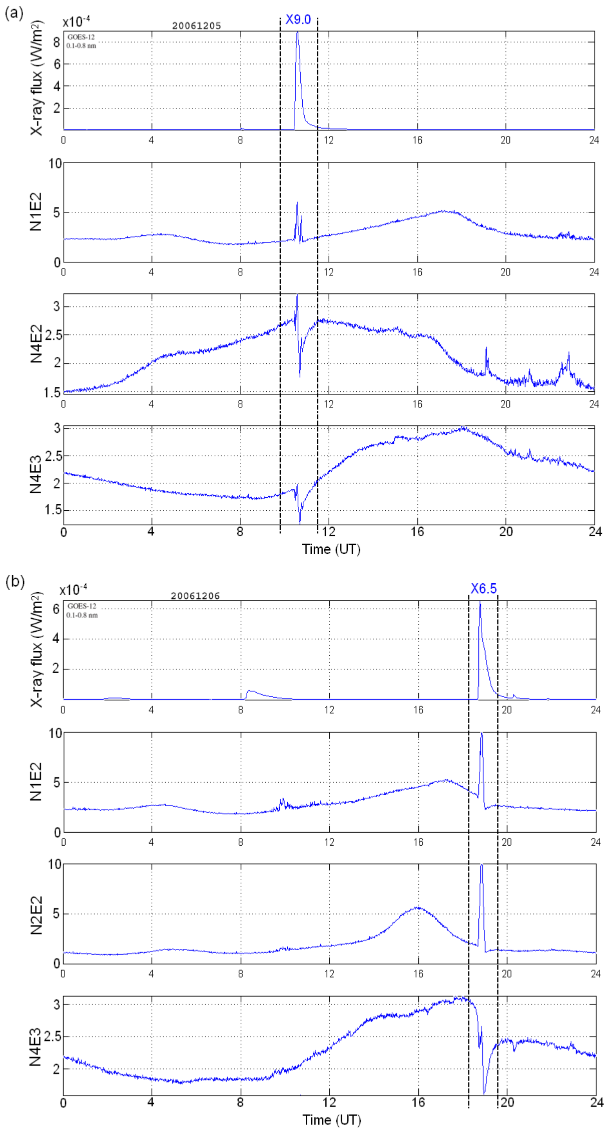


**Fig. 3** - (a) X-ray flux and signal from three riometer antennas for the X-flares on 05 and (b) 06 December, 2006. The period of sudden effects in the ionosphere caused by flare are indicated by dotted vertical lines.

The X-ray flux between 1 and 8 Å from GOES-12 and three components of the geomagnetic field (H, D and Z) for the 15/04/2001 and 04/11/2003 are represented in the Fig. 4a and Fig. 4b, respectively. During the sudden x-ray flux variation the impulse H-component were always positive in accordance with Rastogi, 1993. The largest crochet in the H component during the studied period was on 15 April 2001 at 13:50 UT (10:50 LT) with X-ray intensity of X14.4. The geomagnetic components variation was ~0.0022% for H, ~60% for D and only ~0.0004% for Z. This result is similar to the result of the event on 7 August 1972 analyzed by Rastogi, 2003. During the three phases of the flare, the variation of the induced ionospheric current is proportional to the flare evolution. For the period of the flare (selected in the Fig.4b), the relationship between the H-component variation due to SFE against the X-ray flux by GOES-12 are showed in the Fig. 5. A linear relation between ΔH and X-ray is clearly seen, indicating that the ionospheric current intensification occurs next to the flare time and develops proportional to the flare. Some saturated data in the GOES X-ray detector are indicated by circles over the red line. Based only on the ionospheric D-region response, Thomson et al. (2005) estimated the flare peak as X45±5. These solar flare effects can be very useful in understanding the electromagnetic induction effects and the ionosphere currents on the various components of the fields at the station.

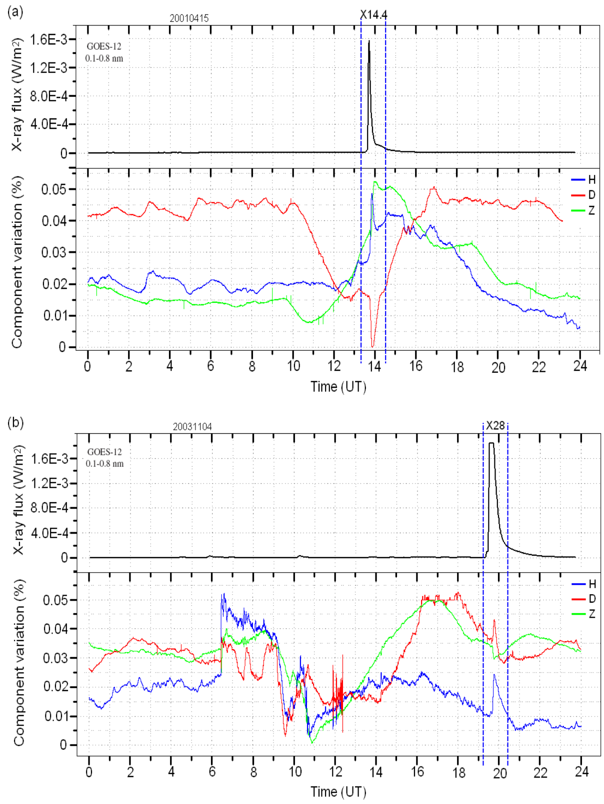


**Fig. 4** - X-ray flux and the three components of the geomagnetic field (H - blue, D - red, Z - green) for the days (a) 15/04/2001 (X14.4) and (b) 04/11/2003 (X28), respectively.

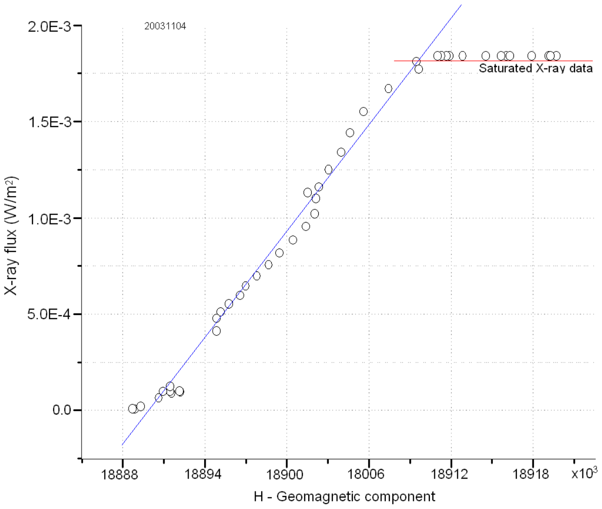


**Fig. 5** – Correlation between the amplitude of the SFE in H component at SSO and the X-ray flux by GOES-12 during a solar flare on 4 Nov. 2003. The circles over the red line indicate saturated data.

**Conclusions**

For the period of maximum and declining of solar cycle 23, the data from the riometer and magnetometer had significant importance to the study of the Solar-terrestrial interaction. In this work many effects in the Ionosphere are detected during the Solar flare. With the SSO magnetometer we identified some events with a sudden change in the components of the geomagnetic field caused by X-ray flares. With this data we verify the large effects on the ionosphere next near local noon (15:00 UT). In the cases investigated, the H component was always positive. During the solar flare X14.4 on 15 Nov. 2001 the amplitude of SFE was 230 nT in H component. From the analysis of imaging riometer data of SSO, Brazil, the relationship between the ionospheric absorption and X-ray flux, the ionospheric ionization process are almost dominated by the solar flares. The ionospheric absorption intensities, which basically increased with the intensities of X-ray solar flares, are almost proportional to a power law form of X-ray fluxes. With the riometer data it is difficult to obtain clear-cut results for the magnitudes of SID, since the solar radio bursts are superimposed on the ionospheric absorption, produced in association with the emission of X-rays, during the explosive phase of solar flare which begins first. Therefore, it is not simple to estimate the maximum decrease of galactic noise intensity due to the ionospheric absorption because the emission of solar radio bursts which starts before the maximum decrease is not yet observed by the riometer and not recorded.

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