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Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 1029–1035
Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS
www.elsevier.com/locate/jastp

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.
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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.

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