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Features of the solar X-ray bursts related to solar energetic particle events

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Abstract

Solar X-ray bursts appear to be most convincing signatures of particle acceleration during solar flares. It is not clear what part of this population escapes the flare region. Majority of solar energetic particles observed in the space after powerful and long lasting solar flares are probably not connected with flares and assumed to be accelerated by the shocks related to the coronal mass ejections. However, there is a significant correlation between intensity of the X-ray bursts and solar energetic particle energy. The paper considers characteristics of the X-ray bursts followed by solar energetic particle occurrences and those bursts not associated with solar energetic particles. It is shown that correlation between X-ray bursts and solar energetic particles increases with growing of X-ray burst class and solar energetic particle energy. In our opinion, it emphasizes the role of processes in the flare region for solar energetic particles occurrence.

Keywords: Solar energetic particles; Solar X-ray bursts

1. Introduction

A problem of solar energetic particles (SEPs) origin is under discussion during several decades. Beginning from the mid twentieth century, SEPs were believed to be accelerated in solar flares (Duggal, 1979; Forbush, 1946). A direct evidence of proton acceleration up to several GeV is observation of high-energy neutrons and gamma emission in the flare region (e.g., Kocharov, 1983). However, it is not clear whether protons, which have generated neutrons and gamma emission, and protons injected into interplanetary space belong to the same population. There are a lot of arguments that SEPs connected with the long lasting (gradual) flares are accelerated by the shocks related to coronal mass ejections (CMEs), contrary to SEPs originated in the impulsive flares, which are generated in the flare region (e.g., Gosling, 1993; Reames, 1999 and references therein). Some researches hold to the idea that both flare and CME-related shock contribute to SEP generation (e.g., Cane, 2001; Kocharov and Torsti, 2002). Till now, there is no solar signal that unambiguously points to the SEP injection into the interplanetary space. The highest correlation ($r = 0.79 \pm 0.08$) is observed between SEP events ($E > 100$ MeV) and solar X-ray burst (XRB) rates on the yearly basis (Bazilevskaya et al., 2003). X-ray bursts are a good indicator of power released in the flare process. However, number of XRBs is hundreds times larger than that of SEP events. Here we try to find XRB features, which are associated to SEP generation.

2. X-ray bursts of various classes and solar energetic particle events

We studied relationship between solar proton events and solar XRBs of various classes on the base of

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Catalogues (Akiniyan et al., 1983; Bazilevskaya et al., 1986, 1990; Sladkova et al., 1998) and GOES observations (<http://spidr.ngdc.noaa.gov>). The data on XRB for 1976–2003 were taken from (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/XRAY_FLARES/). We considered SEP events with protons of different energy, namely, those observed by (1) neutron monitors (ground level enhancements, GLEs, $E > 500$ MeV, $J \sim > 0.1$ cm^{-2} s^{-1} sr^{-1}), (2) balloon-borne detectors ($E \sim > 100$ MeV, $J > 0.5$ cm^{-2} s^{-1} sr^{-1}), and (3) spacecraft-borne detectors ($E > 10$ MeV, $J > 1$ cm^{-2} s^{-1} sr^{-1}). Here, J is proton intensity in the maximum of the intensity-time profile of the SEP event. By removing events recorded at balloons from the SEP event list recorded at spacecraft, we isolated events in the range of 10–100 MeV. Similarly, we isolated events in the range of 100–500 MeV using the data of balloons and neutron monitors observations.

Association of SEPs with XRBs was examined using a superposed epoch technique. As an example, Fig. 1 shows averaged daily rate of the XRBs of the X class (magnitude of the peak burst intensity $I \geqslant 10^{-4}$ W m^{-2}) on the day of SEP event beginning, 10 days before, and 10 days after the SEP event. The rate of XRBs of the X class increases by a factors of 3, 4, and 6 for the SEP events with $10 \leqslant E < 100$ MeV, $100 \leqslant E < 500$, and $E > 500$ MeV, respectively.

Similar procedure was performed for XRBs of various classes. The ratio of the XRB rate on the SEP event day to the mean XRB rate on ±10 days relative to a SEP event, R, was chosen as a measure of connection between SEPs and XRBs.

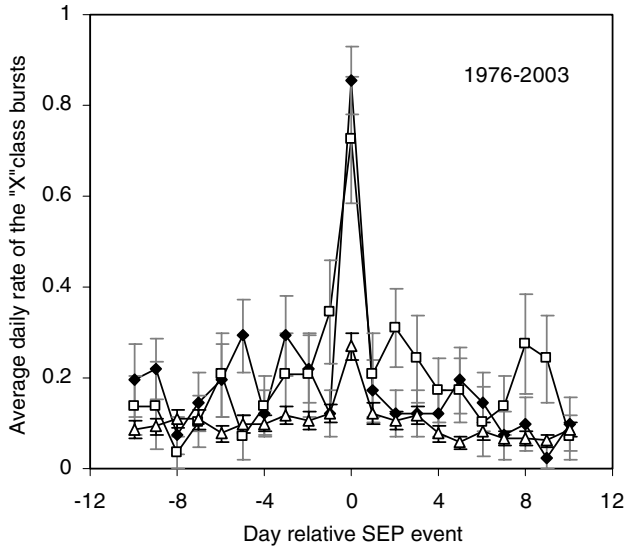

Fig. 1. Results of superposed epoch analysis of the daily rate of XRBs of the X class. Zero days are the days of a SEP event occurrence. Triangles – for SEP events with <100 MeV protons; squares – SEP events with 100–500 MeV protons; rhombs – events with >500 MeV protons (GLEs).

Fig. 2 presents the R values vs. XRB intensity I for the SEP events with different energy of solar protons. The R values are around 1 for $I < 10^{-4}$ W m^{-2} with exception for the less energetic ($E < 100$ MeV) SEP events. Therefore, the SEP events with >100 MeV protons are practically not connected to XRBs of the M class. The R value grows as the XRB intensity increases, especially for GLEs ($E > 500$ MeV). The XRBs of X5 class ($I > 5 \times 10^{-4}$ W m^{-2}) occur ~8 times more often on the GLE day than without GLEs. Indeed, almost all GLEs associated with flares on the visible solar disc followed the XRBs of X class, ~30% of GLEs being connected to XRB of >X5 class. The R value for the SEP events with <100 MeV protons increases at $I > 5 \times 10^{-5}$ W m^{-2}, reaches maximum at $I = (2–5) \times 10^{-4}$ W m^{-2} and decreases at larger I since SEPs with $E > 100$ MeV dominate in events accompanied by the XRBs of >X5 class.

Fraction of the XRBs connected to SEP events is growing with increase of XRB intensity. More than 20% of the XRBs in the interval $10^{-4} \leqslant I < 2 \times 10^{-4}$ W m^{-2} are followed by SEP events (of all energies). In the interval $2 \times 10^{-4} \leqslant I < 5 \times 10^{-4}$ W m^{-2} and for $I \geqslant 5 \times 10^{-4}$ W m^{-2} the XRBs associated with SEP events make 35% and 53%, respectively.

Thus, relation between SEP events and XRBs strongly depends on the SEP energy and the class of XRB. For the SEP events with >100 MeV protons only XRBs with intensity $I \geqslant 10^{-4}$ W m^{-2} (X class) are important. The connection increases with the growth of particle energy and XRB class being most close for the GLEs and the XRB of >X5 class. Connection to XRBs of SEP events with <100 MeV protons is rather weak. The number of coincidences between such SEP events and the XRBs of X class is three to four times larger than expected accidentally, although for the M class the coincidence may often be accidental because of great rates of both such SEP events and such XRBs. Relationship between the SEP events with protons of various energy and the XRBs of

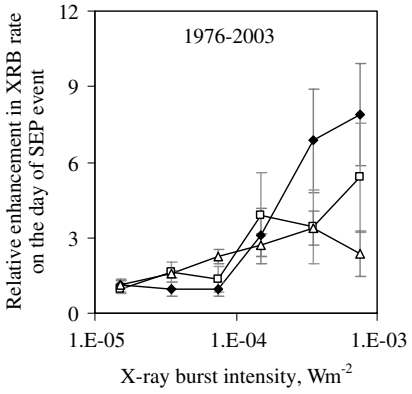

Fig. 2. Ratio of the XRB rate on the day of a SEP event to the average XRB rate during 10 days before and 10 days after a SEP event vs. XRB intensity. Legends are the same as in Fig. 1.