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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.

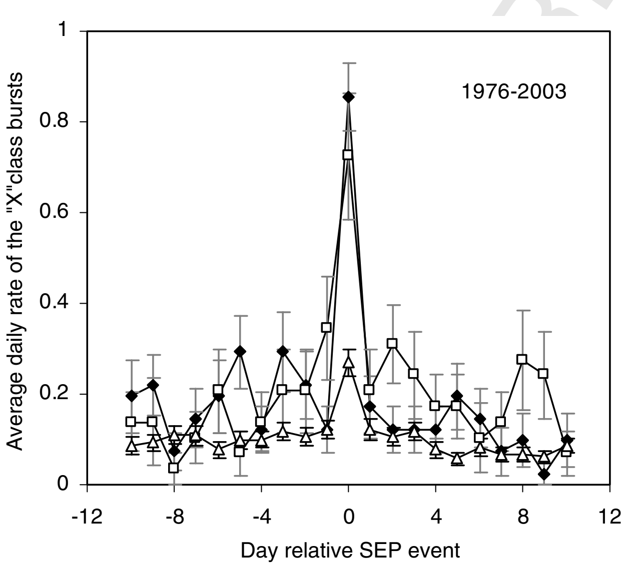

Fig. 1. Results of superposed epoch analysis of the daily rate of XRBs of the X class. Zero days are the days of a SEP event occurrence. Triangles – for SEP events with <100 MeV protons; squares – SEP events with 100–500 MeV protons; rhombs – events with >500 MeV protons (GLEs).

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

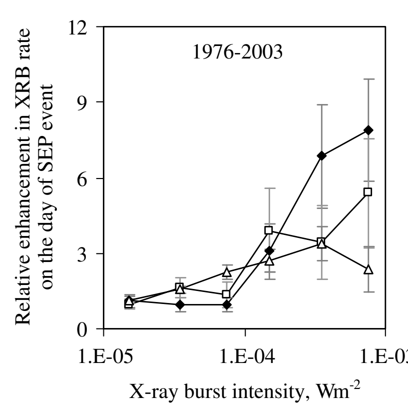

Fig. 2. Ratio of the XRB rate on the day of a SEP event to the average XRB rate during 10 days before and 10 days after a SEP event vs. XRB intensity. Legends are the same as in Fig. 1.

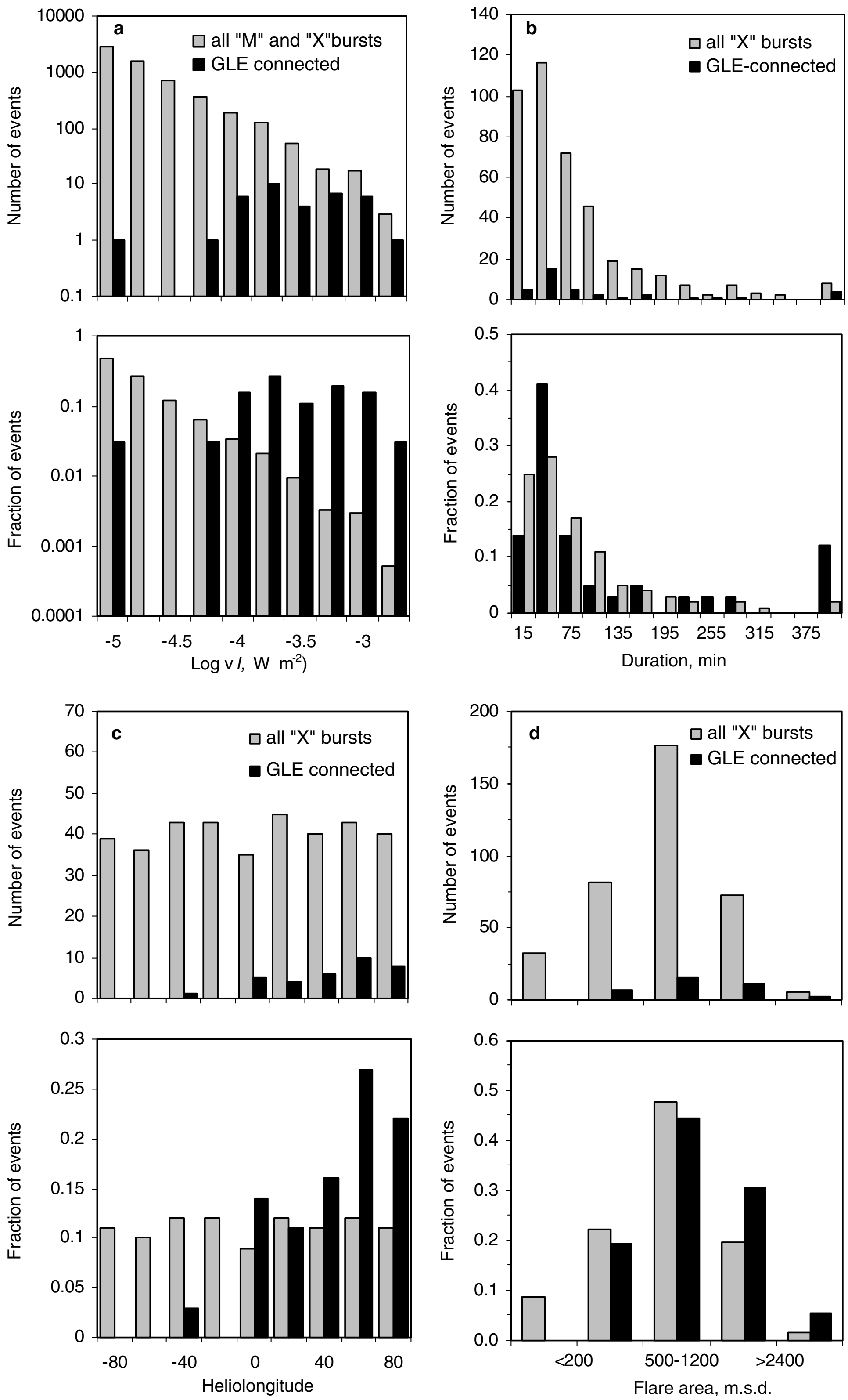

Fig. 3. Distributions of XRBs over various parameters. Upper panels of each figure – distributions of number of events; lower panel – distributions of fraction of events. Light bars – all XRBs, dark bars – GLE associated bursts. (a) Distribution of XRBs over the X-ray peak intensity. Only M ($10^{-5} \leqslant I < 10^{-4}$ W m^{-2}) and X ($I \geqslant 10^{-4}$ W m^{-2}) classes are taken into consideration. (b) Same as in Fig. 3(a), but for XRB duration. Only bursts of X class are considered. (c) Distribution of XRBs over the Hα flare heliolongitude. Only bursts of X class related to the Hα flares are considered. (d) Same as in Fig. 3(c) but for the Hα flare area.

various classes is considered in more detail for 1975–2001 in (Bazilevskaya et al., 2004).

3. Features of X-ray bursts followed by ground level enhancements

It is interesting to compare features of XRBs followed by the SEP events and those not followed by the SEP events. Only GLEs were considered here since they are connected to XRBs most closely. The most powerful XRBs among those occurred before or during a GLE within 2.5 h assumed to be associated with a GLE. Data on XRBs are available from 1975 to 2003. During this time 41 GLEs were recorded including four events related to the active regions well behind the solar limb. The reminder of 37 GLEs was connected with the XRBs.

Distributions of XRBs associated with GLEs over their main parameters are presented in Figs. 3(a)–(d) together with distributions of all XRBs. Top panels of each Figure give distributions of real numbers of events. Here the real proportion of all XRBs and those associated with the GLEs is clearly seen. Bottom panels of Figs. 3(a)–(d) give the same distributions for the fractions of events, i.e., a ratio of events with a given feature to the total number of all XRBs or total number of the GLE connected XRBs. This emphasizes characteristics of the distributions of the GLE connected XRBs comparatively to those of all XRBs.

The distribution of the GLE connected events over the burst intensity (Fig. 3(a)) is rather flat against the falling distribution of all XRBs. As the XRB intensity increases the ratio of GLE connected event number to all XRBs also grows making ~35% for events ⩾X5 class. All GLEs (1976–2003) except for three events (21.08.1979, 10.05.1981, and 26.12.2001) followed the XRBs of the X class. This enabled us to consider further the features of only X class XRBs.

Fig. 3(b) shows the distribution of XRBs over burst duration. Last bin contains all events lasting more than 400 min. Again, the portion of GLE connected events increases with growth of the burst duration. Owing to long lasting events the mean duration of GLE connected XRB is almost twice longer than the mean duration of all X class XRBs in spite of the fact that the main parts of both distributions over burst duration are rather similar to each other.

For next consideration, we select only XRBs occurred simultaneously with the Hα flares to examine their heliolongitudinal and area distributions. Among the X-class, ~90% of all events and all GLE connected XRBs are associated with the Hα flares. Fig. 3(c) confirms a well-known fact that GLEs can preferably be observed after parent flares of the western heliosphere (Bazilevskaya et al., 2003). Heliolongitudinal distribution of all XRBs is flat. Distributions of XRBs over Hα flare area (Fig. 3(d)) are rather similar for all and GLE connected XRBs, but GLEs avoid the flares with area less than 200 m.s.d (importance "S").

It can be concluded that majority of GLEs occurs after most intense and long lasing XRB, which are generated simultaneously with western Hα flares of area above 200 m.s.d. These features are indicative of a powerful XRB and correlate with each other. It is not clear as yet what parameter is most important for the GLE occurrence.

Both XRBs and, especially, GLEs occur episodically and it is useful to examine and compare their time histories. Since GLE rate is much lower than that of XRBs, we tried to put some limitations on the XRB parameters to achieve the best correlation between GLE and XRB occurrences. All X class bursts were considered since the distribution of the GLE connected XRBs over burst intensity is almost flat (Fig. 3(a)). It is also clear that there is no duration threshold for the GLE connected XRBs (Fig. 3(b)). Taking only XRBs of the X class associated with western Hα flares and area of above 200 m.s.d. area (importance "1" and higher), we obtained Fig. 4 where the time of every GLE (from western parent flare) and every XRB (with mentioned limitations) is depicted. Northern and southern events are

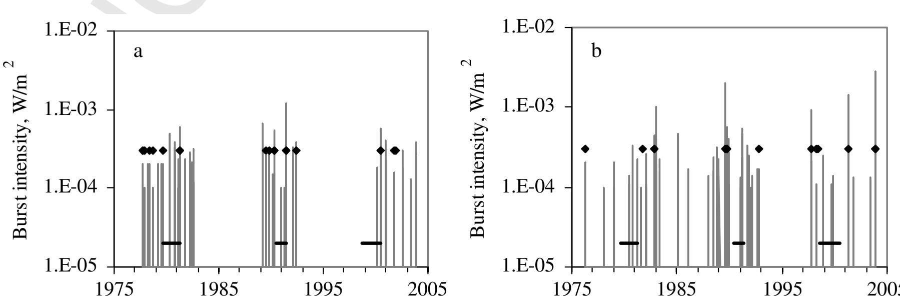

Fig. 4. Time history of GLEs (black rhombs indicate time of occurrence) and XRBs of X class (height of vertical bars indicates a burst intensity) associated with western Hα flares of area above 200 m.s.d. for the northern (a) and southern (b) events. Dark horizontal bars mark the Gnevyshev Gaps in the GLEs occurrence.

given separately. The number of XRBs with the limitations chosen is four times larger than that of GLEs, but the main peculiarities of the GLE occurrence can be traced in the XRB history. In particular, some XRB rarefactions are seen around 1980, 1990, 1999. GLEs were absent in these periods in spite of high solar activity demonstrating the so-called Gnevyshev Gaps (Bazilevskaya et al., 2005; Storini and Pase, 1995).

4. Discussion and conclusion

There is a significant correlation between the solar X-ray bursts (1–8 Å) and SEP events when the most intense bursts (X class) and most energetic SEP events (GLEs) are considered. The rate of the X class XRBs is six times higher on a GLE day than on the preceding and following days. More than 90% of GLEs associated with the flares on the visible solar disc followed the XRBs of the X class. The XRBs followed by GLEs are more intense and longer lasting, and they are associated with Hα flares of large area, predominantly on the western solar hemisphere. Although the number of such XRBs is about four times larger than that of GLEs their time history bears some resemblance with the GLE occurrence including peculiarities inside an 11-year cycle (Gnevyshev gaps). Since XRBs are closely related to the energy release in the flare region we believe that the correlations found argue for the importance of the solar flares for the acceleration of SEP up to relativistic energies.

The correlation becomes lower when the less intense XRBs and less energetic SEPs are concerned. The SEPs with energy below 100 MeV are mostly connected to the M class XRBs. However, the numbers of such XRBs and such SEP events are so high that the accidental coincidence is rather probable (Bazilevskaya et al., 2004). This conclusion is drawn from a statistical study and does not exclude a real connection between an M class XRB and a SEP event in some cases. Nevertheless, it seems that XRBs do not play a significant role in acceleration of SEP to energies below 100 MeV. A certain correlation between the occurrence of the low energy SEPs and XRBs of the X class may point to the flare energy release and the CME occurrence with subsequent shock acceleration.

Acknowledgments

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