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Cycle 23 flare temperatures and emission measures as derived from *GOES* X-ray data

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Abstract

Solar X-ray observations recorded by the series of geostationary observational environmental satellites (*GOES*) are analyzed over a time interval of the 23rd solar cycle. Statistical analysis of a large database of *GOES* events is performed. Temperature and emission measures derived based on *GOES* fluxes for all events are compared and analyzed. A specific application of *GOES* X-ray measurements to space weather forecasting is discussed. Namely, using an information about maximum temperature and maximum emission measure of a given flare one can assign a probability to this flare of being ''non-SEP associated''.

Keywords: Sun; Flares; Energetic particles

1. Introduction

The geostationary operational environmental satellite program is a joint effort of National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). The *GOES* program formally began in 1975 with the launch of *GOES-1* satellite from Cape Canaveral. At present, the *GOES* system consists of *GOES-12* operating as *GOES*-East in the eastern part of the constellation at 75°W longitude, and *GOES-10* operating as *GOES*-West at 135°W longitude.

The *GOES* spacecraft are mainly meteorology observing satellites but all of them have been also equipped with so-called space environment monitor (SEM) system for measuring solar X-rays, energetic particles, and magnetic field at the geostationary ~35 000 km altitude orbit. In what follows the X-ray data and the particle fluxes from *GOES*-SEM systems are used to study space weather related issues.

The results presented here may allow for assigning a probability of being ''non-SEP associated'', for any flare observed by *GOES*. This can be done ''on-line'' after respective flare peak when maximum values of temperature and emission measures are determined. In turn it allows for elimination of large amount of the events from consideration as SEP productive.

2. Data description and analysis

We have analyzed 13 814 events (from the time interval 1996–2006) of increased solar X-ray flux

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classified as C, M and X flares in standard *GOES* event classification routine. The flare *start* time is defined by NOAA as the first minute in a sequence of 4 min of monotonic flux increase in *GOES* 0.1–0.8 nm channel. The *end* time corresponds to the moment when the flux decays to a midpoint between the flux maximum and the pre-flare background level. During the analyzed period in the *GOES* event database we found 116 flares of X-class, 1340 of M-class and 12 358 flares of class C.

For all ~14 000 events we determined time profiles of temperatures and emission measures. Both the temperatures and the emission measures were calculated from pre-flare signal subtracted fluxes in *GOES* 0.05–0.4 and 0.1–0.8 nm channels. The temperatures and emission measures were derived in the isothermal approximation by applying the flux-ratio technique. Calculations were made using the standard routine goes_chianti_tem.pro available from the *SolarSoft*[1] package. From the calculated time profiles of temperatures and emission measures their maximum values for all events were determined. These maximum values characterizing each of the analyzed flares are used further in this paper.

Using the above-mentioned NOAA definitions of event *start* and *end* time we estimated duration for each particular flare as a difference between the *end* and the *start* time.

During the analyzed period, one can distinguish 78 flares in the *GOES* flare database followed closely in time by highly increased flux of energetic protons—i.e. the proton events at the Earth orbit. Proton fluxes are integral 5-min averages for energies higher than 10 MeV, given in particle flux units (pfu, $1\,\mathrm{pfu} = 1\,\mathrm{proton\,cm^{-2}\,s^{-1}\,sr^{-1}}$), measured by *GOES* spacecraft at geosynchronous orbit. A list of identified proton events and associated solar flares[2] is maintained by NOAA Space Environment Services Center (SESC).

SESC defines the *start* of a proton event to be the first of three consecutive data points with fluxes greater than or equal to 10 pfu. The *end* of an event is the last time when the flux was greater than or equal to 10 pfu. Solar energetic particle (SEP) events are widely studied at present because they cause a major space weather threat. Two classes of SEP events were distinguished (e.g., Reames, 1999). The first class is formed by events associated with a short lasting flares (duration shorter than 1 h) and called impulsive SEP events. The second class, gradual SEP events, consists of events following in time flares of duration longer than 1 h. Nowadays the terms impulsive and gradual are applied to distinguish the duration time scales of SEP events (Kahler et al., 2001; Reames, 2002) rather than to their associated flare duration. All the 78 SEPs selected for analysis are associated to flares. Almost all of them were also accompanied by coronal mass ejections (CME). The majority of these SEPs were of impulsive type (52 events) and only 26 events were of gradual type.

It was observed (Sylwester et al., 1996) that there are significant differences in thermodynamic characteristics of the SEP associated flares in comparison with the non-SEP flares. Namely in the log–log plots of maximum temperature versus maximum emission measure the SEP flares formed a straight trend line below the trend line for the non-SEP flares. This bifurcation may be useful in SEP events prediction algorithms. In particular a large amount of the events can be eliminated from consideration while forecasting the SEPs.

Here, we performed similar analysis using much larger sample of flares observed by *GOES* over a solar cycle in order to re-examine the differences in thermodynamic characteristics of SEP associated flares and those for which no following proton activity was detected. We also checked if the above-mentioned differences in thermodynamic characteristics of SEP flares depend on their impulsive or gradual character.

We fitted the linear model to the calculated maximum values of temperature and emission measure using a robust least absolute deviation method. The fit was performed with the use of *LADFIT* function accessible in the interactive data language (*IDL*) environment. This function also calculates the mean of the absolute deviation of the fit which can be used to estimate the fit uncertainty.

The fit was made separately for "non-SEP" flares and SEP associated flares. These fits and their populations are presented in Fig. 1. In addition, for SEP associated events, two independent fits were made for gradual and impulsive events (see Fig. 2).

In Fig. 1 the log–log plot of the maximum temperature versus the maximum emission measure for the set of ~14 000 events is presented. It is seen that SEP and non-SEP flares are distributed around two nearly parallel trend lines. The trend line for SEP associated flares is (about 3 MK) below the

[1]http://www.lmsal.com/solarsoft/.

[2]http://umbra.nascom.nasa.gov/SEP/.