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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 pfu = 1 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/.

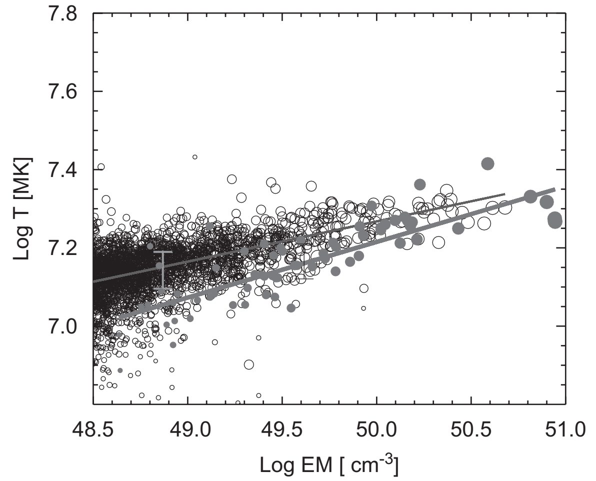

Fig. 1. The log–log plot of flare maximum temperature (T) versus flare maximum emission measure (EM) for considered *GOES* flares. The non-SEP flares are plotted as black open circles. SEP associated flares are plotted as gray filled circles. Lines of trend for both flare populations are over-plotted (in thin-gray line for non-SEP flare and in thick-gray line for SEP flares). Lines are nearly parallel. The slopes of these lines are 0.14 and 0.16 for non-SEP and SEP flares, respectively. The SEP trend line is, however, shifted down by as much as 3 MK on average below the trend line of non-SEP flares. The circle diameters characterize respective flare magnitudes. They are proportional to the logarithm of the flare peak intensity in *GOES* 0.1–0.8 nm channel. The black and gray bars superimposed on the plots have lengths twice the mean absolute deviation of the fit and its population. The bars are placed at the mean (Log EM, Log T) position in the population to which a particular trend line was fitted.

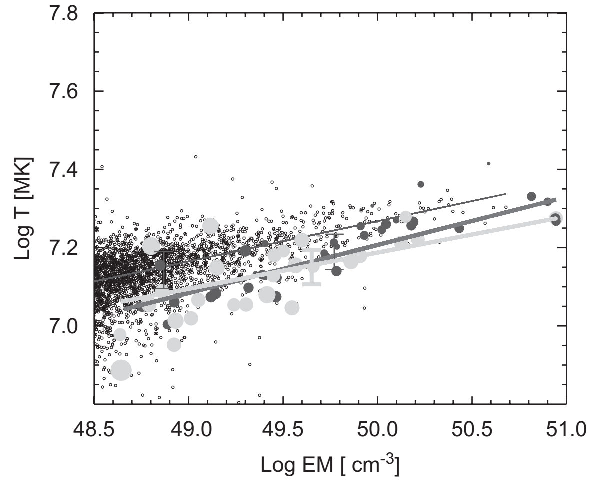

Fig. 2. The log–log plot of flare maximum temperature (T) versus flare maximum emission measure (EM) for considered *GOES* flares. The non-SEP flares are plotted as open circles of equal size. SEP associated flares are plotted as filled light-gray circles (gradual flares) and filled dark-gray circles (impulsive flares). Line of trend for non-SEP flares is plotted in thin-gray solid line. Diameters of gray circles are proportional to the logarithm of flare duration. Overplotted in thick lines are trend lines for impulsive events (dark-gray line) and gradual events (light-gray line). Vertical bars superimposed on the plots have lengths twice the mean absolute deviation of the fit and its population. The bars are placed at the mean abscissa and ordinate values of the population to which each trend line was fitted.

trend line for the non-SEP flares. This shift is particularly well visible for flares of lower *GOES* class. Flares accompanied with SEPs are generally cooler than non-SEP associated flares as seen on the T versus EM diagrams in Fig. 1.

The difference is a bit larger for the gradual SEP associated flares (compare the thin-gray, light-gray and dark-gray thick lines in Fig. 2). It is worth to note that the inclination of trend line for the gradual SEP associated flares is similar to this derived for non-SEP flares. However, the trend line is shifted down as for the impulsive events. Impulsive events have greater inclination of their trend line in comparison to gradual events.

This property can be used to reject a significant amount of flares while forecasting SEP events. Such a rejection would eliminate many events from analysis but would have some uncertainty due to the fact that some SEP associated flares could be eliminated too.

For instance, if we rejected all the events which have the Log T values twice the mean absolute deviation above the trend line for SEP associated flares (thick-gray line in Fig. 1) we would eliminate 9767 events (more than two-thirds of the entire *GOES* flare sample) as non-SEP associated. In this case we would also eliminate 11 SEP associated flares what makes about 15% of the entire SEP flare sample investigated here (78 events).

However, if we rejected the events with Log T values triple the mean absolute deviation above the trend line for SEP associated flares we would have 6416 (about a half of entire flare sample) events eliminated with only five SEP associated flares. In this case the missed SEPs would amount to only 6% of the entire SEP flare sample investigated.

We have checked also the compatibility of the SEP associated flares to the fits in Fig. 1. It appears that 47 from analyzed 78 SEP associated flares are compatible with the fit line for SEP events within the error. Only 25 SEP associated flares are compatible with the fit line for non-SEP associated flares within that fit error. There also are eight SEP associated flares which are compatible with both fits and lay in the area in which error bars of fits overlap.

Some individual flares that do not produce SEP may well be compatible with the fit of the SEP-producing flares (see Figs. 1 and 2). For these events an additional criterion (which is now under investigation) must be necessarily provided in order to distinguish them from SEP flares.

A physical explanation for the effect observed is not obvious. One of the possibilities could be that for the SEP associated flares, relatively greater part of energy released from the magnetic reconfiguration is transformed into kinetic form (bulk motion of particles flowing outwards). Such a shift in maximum temperature could also indicate that a part of the energy released in SEP associated flares is not dissipated in the solar atmosphere and goes to particle ejection/acceleration.

The present study is a first step of a more advanced analysis of flare SEP and non-SEP associations which is going to be done using the spectral data from REntgenovsky Spektrometr s Izognutymi Kristalami (RESIK) instrument (Sylwester et al., 2005).

3. Conclusions

The results presented in this research may allow for assigning a probability of being "non-SEP associated", for any flare observed with *GOES* X-ray monitor. This can be done "on-line" after respective flare peak when maximum values of T and EM are determined i.e. well in advance of a possible arrival of accelerated particles to Earth. It appears quite possible that the other flares, shown as points in the T–EM diagram below the SEP trend line (cf. Fig. 1) were also the SEP associated events. In this case SEPs could have been however undetected missing the Earth on their paths.

The shift observed as a difference in the trend line positions can provide a quantitative base to reject a large amount of flares from being a source of SEPs. This can improve the speed and reliability of the SEP forecast methods.

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