Study on the Features of the SEP Solar Origin Based on Microwave Observations

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Abstract.

We present the results on the analysis of microwave (MW) emission in solar flares related to strong solar energetic particle (SEP) events observed during the 23rd solar cycle. The parameters of the MW spectrum were used as indicators of acceleration processes during solar flares. The magnetic topology of the active regions (ARs) that produced the flares were taken into account by the approach suggested by Abrameko et al. [2018]. We found that during their evolution most of the ARs related to proton-rich SEP events violated at least one of the classical sunspot group evolution laws (Hale` s law, Joy`s law et cetera). However, the statistical study of all ARs of the cycle revealed the domination of normal ARs. The dependences between SEP events and MW indicators of the acceleration process for different groups are studied and discussed.

Introduction

The nature of the solar sources of solar energetic particle (SEP) events has not been fully understood nowadays (see, *Klein and Dalla,* 2017). There is no definitive answer to a very important question – are the charged particles accelerated during flares in the solar atmosphere or on shock waves generated by coronal mass ejections (CME)? Or do both of these mechanisms contribute to acceleration in different ratio? Why some active regions (ARs) are sources of a large number of solar geoeffective events, while others are not? The X-ray and gamma-ray emissions are direct indicators of acceleration processes in the solar atmosphere. But since the sensitivity threshold of modern detectors in these spectral ranges is not sufficient for detecting weak fluxes, information about many events is lost. The alternative to direct observations is the observation of microwave (MW) emission that is more sensitive to mechanisms of emission generated by accelerated electrons. However, applying of this type of observation as indicators of the processes of energy release and acceleration of particles in solar flares faces some problems. The first problem is that MW emission is generated by electrons only while the majority of SEP observations deals with protons. However, *Chertok et al.* [2009] showed the close correlation of the SEP proton fluxes and properties of MW emission. The other problem is that the MW flux distribution with frequency could be influenced simultaneously by several physical parameters. For example, the same flux value at the maximum of the spectrum can result from both the magnetic field value at the source and the density of accelerated electron flux. Thus the statistical analysis could get scattering resulted from non-uniform physical/morphological properties of solar sources.

Also, it is difficult to take into account the magnetic morphology of the emission source both as the magnetic topology of the AR. *Abramenko et al.* [2018] analyzed the violating of the classical sunspot group evolution laws for ARs of the 24th solar cycle. The study was done based on line-of-sight magnetograms provided by HMI/SDO and revealed three groups of ARs. The first group (A) consisted of regular ARs followed all the mean-field dynamo laws. They are about half of all analyzed ARs. The second group (B) was formed from the irregular ARs, violating either Hale polarity law or Joy's law or having the leading spot less than the main following spot. It turned out that they are about 25 %. The last group consists of unipolar ARs. These results give us some indicator of the AR's magnetic structure. The current study aims are to check the relation of the different groups with solar sources of proton-rich SEP events and to carry out the statistical analysis of MW emission parameters characterizing the acceleration processes.

Data and analysis

The SEP events with significant proton fluxes and solar flare related to these events were chosen using the catalogue of proton events by *Papaioannou et al.* [2016]. We also need to select events with signatures of non-thermal X-ray emission in order to check the properties of the acceleration processes. Thus, the period of selection should be limited by the observation of one instrument observing in this spectral region. We used data by CORONAS/SONG spacecraft for the period 2001–2005 [*Kuznetsov et al.,* 2014]. This instrument obtained 1D and spectral observations but with high sensitivity to weak fluxes in non-thermal X-ray range. We selected the flares with pronounced response in spectral range above 25 keV. These events should also be simultaneously observed by RHESSI for confirmation of the localization. After the cross-check of the lists, we were left with 24 solar flares that satisfied the selected properties.

The catalogue presents SEP event fluxes of protons with energies above 10 MeV, 30 MeV, 60 MeV and 100 MeV. To increase the statistics, we used the information on the ratio of the maxima of the flux of particles with energies above 10 MeV and 30MeV. The lower value means a higher amount of more energetic protons.

The selected events should also have a response in the MW range. The parameters of the MW spectra were analyzed based on observations of the Radio Telescope Network (RSTN). RSTN [*Guidice et al.* 1981] obtains radio data with a time resolution of 1 s at eight selected frequencies and provides quasi-continuous data coverage over the day. If possible, the Nobeyama radio polarimeters data [*Torii et al.,* 1979; *Nakajima et al.,* 1985] were used for improving the spectral resolution of MW spectra. We used the values of the peak frequency and the electron spectral index as indicators of acceleration processes. The peak frequency is the frequency at which the flux value reaches a maximum. The electron spectral index δ was calculated by the formula $\delta = 1.1 * (\alpha-1.2)$ [*Dulk,* 1985], where α is the MW photon spectral index estimated as the slope of the spectrum at frequencies above the peak frequency.

To study the peculiarities of the AR we used the line-of-sight magnetograms and white-light observations by SOHO/MDI [*Scherrer et al.,* 1995] and EUV observations by SOHO/EIT [*Moses et al.,* 1997]. The considered events took place in 22 ARs during the 23rd cycle and had various topology of the magnetic field. We used criteria which allow us to take into account the peculiarities of the AR's evolution based on the magnetic-morphological classification of ARs. The classification relates to the agreement of bipolar ARs to the basic laws of the mean-field dynamo theory: the polarity law (Hale's law), the law of the tilt latitudinal dependence (Joy's law) and the rule about the ratio of magnetic fluxes/areas of leading and following sunspots. The criteria distribute the ARs into the same groups as it was in *Abramenko et al.* [2018].

We carried out, both, analysis of all ARs of the 23rd solar cycle and of the selected ARs. The results are presented as diagrams in Fig. 1. One can see that the distribution between the different groups (A, B and U) is the same as it was during the 24th solar cycle [*Abramenko et al.*, 2018]. However, most of ARs that were related to SEP events occurred among the ARs violating at least one law (group B). The physical reason for such distribution could be that ARs violating the classic laws should have more complicated magnetic topology. This feature is well known as a factor promoting flare and CMEs productivity of ARs and SEP events as well.

To compare the indicators of acceleration in solar flares according to the MW emission with the ratio of SEP proton fluxes, we divided the events in two groups, A+U and B. The events of the first group occurred in regular ARs, which followed all laws or are unipolar (as rule the remains of leading spots of regular ARs). The magnetic structure in their ARs should be close to classical bipolar or unipolar. The other group consisted of events which turned out in ARs-"violators". Figure 2 presents the plots of the ratio of the maximum of proton flux above 10 MeV to the maximum of proton flux above 30 MeV relative to the peak frequency in GHz of the MW spectrum of the related flare. We can see that events related to ARs from groups A and U show some trend of this ratio to the peak frequency. The SEP events with more energetic protons correspond to the higher value of the peak frequency. The higher peak frequency could be a result of the higher magnetic field in the emitting source or larger fluxes of accelerated electrons. Anyway, this fact confirms the close relationship between acceleration processes in the solar atmosphere during flares and proton abundance of SEP events. But the plot for group B does not show a strong correlation.

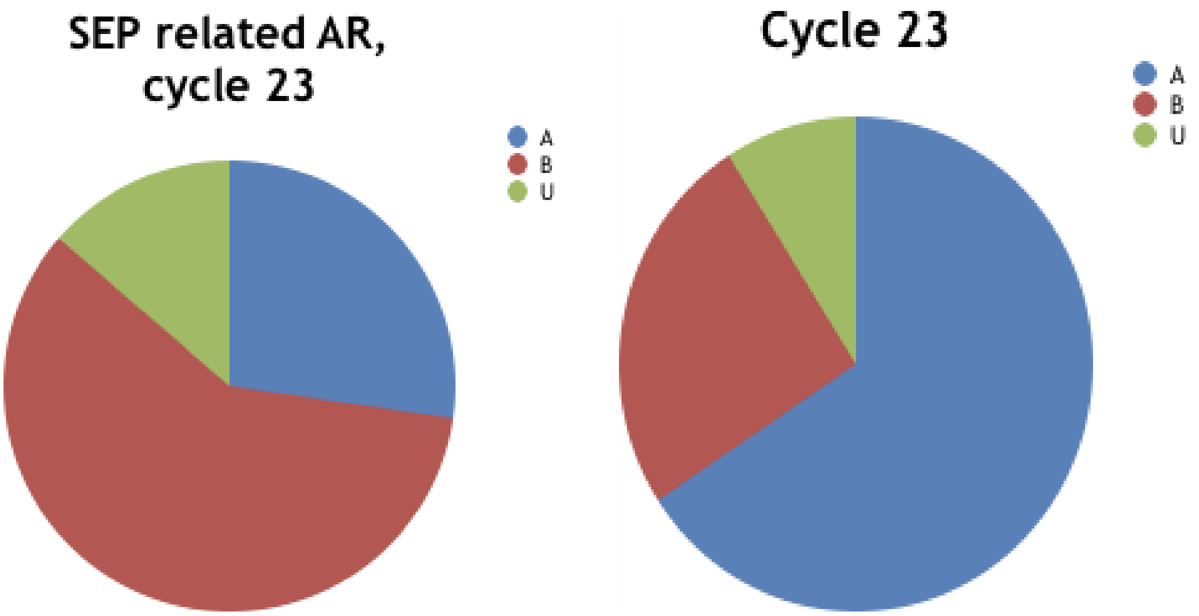

Fig. 1 The diagrams show the ratio of regular active regions (A), the active region violating at least one of the laws (B) and unipolar active regions (U). The left panel shows the ratio for all groups of the 23rd solar cycle. The right panel shows the ratio for active regions related with SEP events with proton fluxes.

The comparison of proton flux ratio in SEP events relative to the electron spectral index is shown in Figure 3. One can see that events related to ARs from group A and U demonstrate some correlation or tendency while the SEP events related to ARs from group B did not. We note that the tendency seen on the left panel of Fig. 2 is in good agreement with results obtained by *Daibog et al.* [1993]. The authors explained the relation of more proton-rich events to solar flares with the soft spectral index by the better possibility of the particle to escape from the higher loops where spectral index should be softer.

We also compared the photon flux ratio in SEP events and CME speed for the same groups (see, Fig. 4). Most of the CME speeds associated with the events of group A and U had the speed of about 1500 km/s and did not show a dependence with the ratio. The behavior of the events related to group B looked complicated and should be studied more carefully.

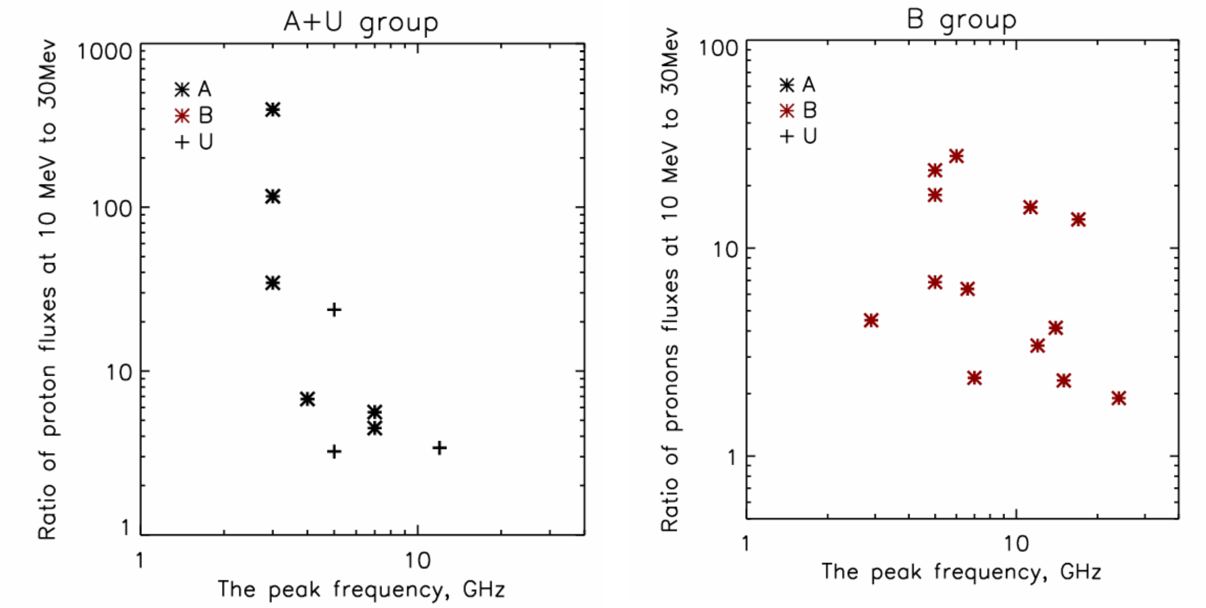

Fig. 2 The ratio of the fluxes at the maximum for protons with energies above 10 MeV to the fluxes of protons with energies above 30 MeV relative to the peak frequency for groups A and U (right panel) and group B (left panel), respectively.

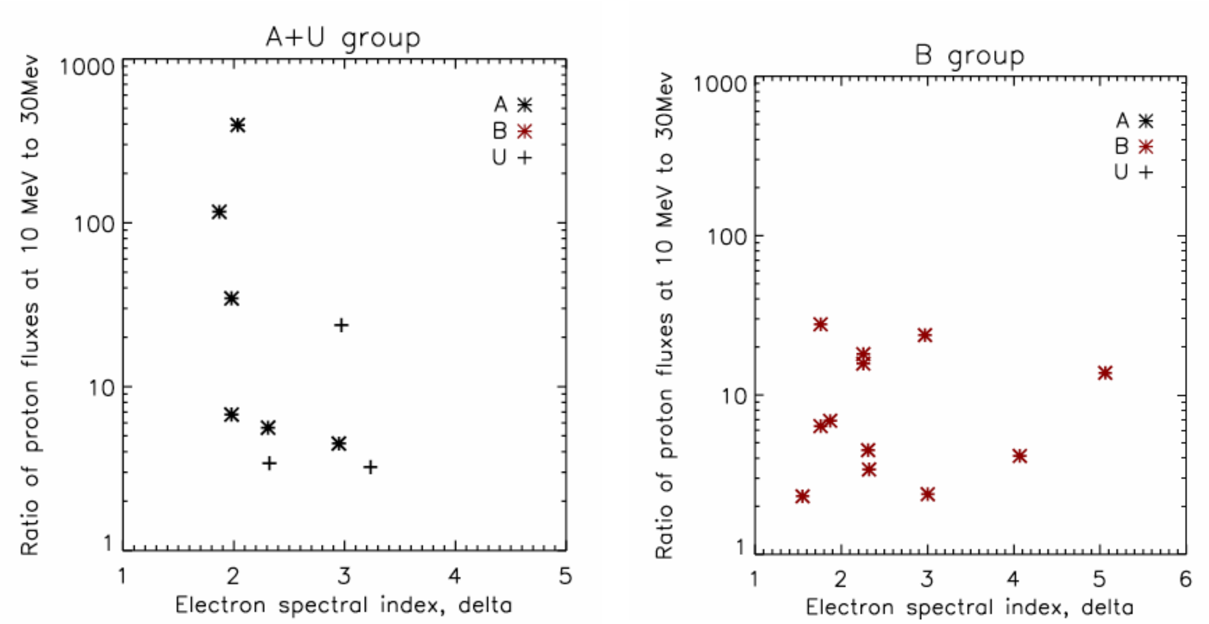

Fig. 3 The ratio of the fluxes at the maximum for protons with energies above 10 MeV to the fluxes of protons with energies above 30 MeV relative to the electronic spectral index for groups A and U (right panel) and group B (left panel), respectively.

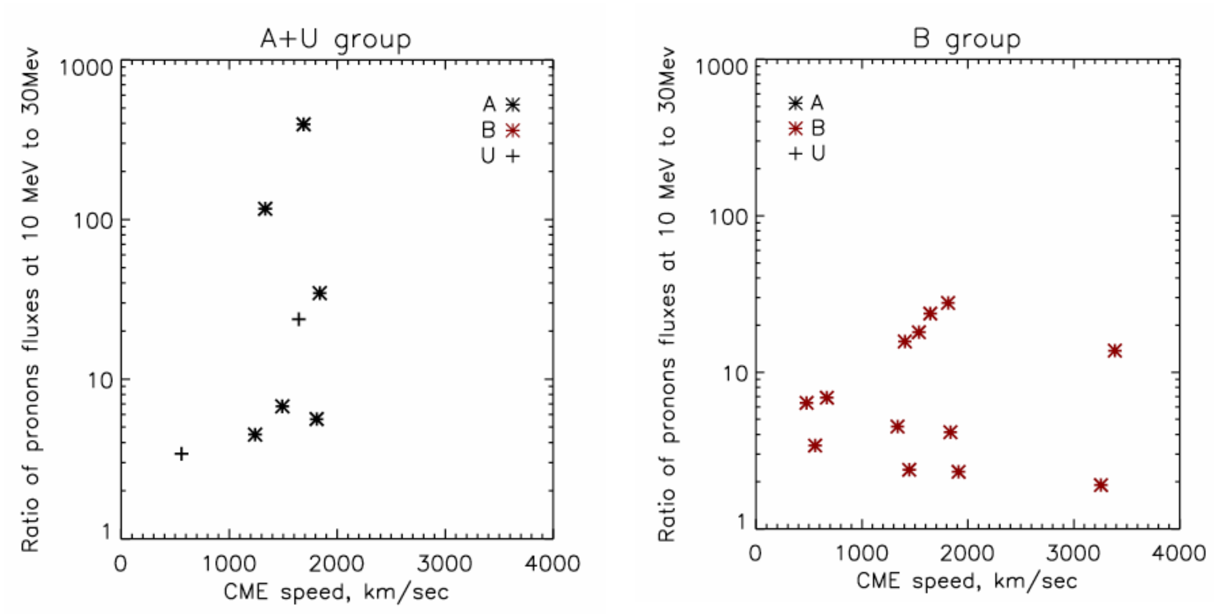

Fig. 4 The ratio of the fluxes in the maximum for protons with energies above 10 MeV to proton fluxes with energies above 30 MeV relative to the projected velocity of CMEs (https://cdaw.gsfc.nasa.gov/CME_list/) for groups A and U (right panel) and groups B (left panel), respectively.

Conclusions

Based on the analysis we make the following conclusions:

Most of ARs related to proton-rich events SEP events occurred in the ARs violating at least one of the classical mean-field dynamo laws (group B). But the statistical study of all ARs of the 23rd solar cycle showed the domination of normal ARs (group A).

Events associated with groups A and U show dependences on the peak frequency and spectral index, predicted by solar flare models and previously obtained by other authors (see, for example, *Daibog et al.,* [1993]).

Events related with ARs of group B do not show any clear dependencies on both the peak frequency and spectral index.

We expect that most of the methods developed based on the "standard flare" model will work for prediction of the SEP productivity of ARs of groups A and U. However, these results require additional statistical study.

Acknowledgment

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