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Analysing of the SEP origins based on microwave emission of solar flares

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Abstract.

We present the results on the analysis of microwave emission in solar flares related to strong solar energetic particle (SEP) events observed during the previous solar cycle. The target of the work is to find criteria based on the solar flare features that would allow us to separate the SEP events into groups with more homogeneous physical/topological properties. In the current study, we compared peak frequency of microwave spectra and spectral index with spectral characteristics of SEP proton fluxes. The two groups of events related to the value of the peak frequency are found. We discuss revealed tendencies and physical reasons of the two population appearances.

Introduction

Magnetic reconnection in solar flares and the shock waves driven by coronal mass ejections (CMEs) are two main models for particle acceleration in the solar corona suggesting the explanation of solar energetic particle (SEP) event properties. All arguments pro et contra are based on correlation analysis between selected parameters of the SEP origin (flares and CMEs) and the in situ particles. The microwave (MW) emission is a sensitive indicator of particle acceleration and energy release processes in solar flares. Earlier studies of solar sources of SEP events used different spectral parameters of this kind of emission as indicators, see for example, [Daibog et al., 1993]. However, MW emission is sensitive to several parameters simultaneously. For example, the flux at a maximum of the spectrum could be a result of the electron flux or magnetic field strength (see Stähli et al., [1989], for example). If we compare this parameter with the properties of SEP particles, then we may face with the mixture of two populations. Thus the dependence related to the acceleration process is blurred.

The aim of this work is the comparison of spectral properties of the SEP events related to solar flares with MW spectral parameter and separation the events to groups with more close physical features. We chose the peak frequency of the microwave spectrum as the parameter characterizing the properties of MW emission. It is the frequency where flux is maximal in the MW spectrum. This parameter is mainly sensitive to the magnetic field strength. It is less affected by the angle of view and electron flux.

Data

We based our analysis of radio spectra on observations of the Radio Solar Telescope Network (RSTN). RSTN [Guidice et al. 1981] is providing radio data with 1 s temporal resolution at eight selected frequencies (245, 410, 610, 1415, 2695, 4995, 8800, 15400 MHz). The four worldwide stations (the Learmonth, (Australia), San Vito (Italy), Sagamore Hill and Palehua (USA)) allow having quasi-similar data 24 hours per day. For some events, we complemented our analysis by data of Nobeyama RadioPolarimeters (NoRP). The spectropolarimeter [Torii et al., 1979; Nakajima et al., 1985]. provides the intensity and circular polarization at six frequencies (1, 2, 3.75, 9.4, 17, & 35 GHz) and the intensity only at 80 GHz .The time resolution is 0.1 sec in the flare mode, and 1 sec in the background mode (no 80 GHz data). We used the catalog of strong energetic proton events by [Papaioannou et al,. 2016] for selection of the events that occurred within 2001–2005. The catalogue presents the fluxes of SEP events for the energies above 10 MeV, 30 MeV, 60 MeV and 100 MeV.

Data processing

There are 61 events with data about SEP (onset time) and associated flare (class, begin and end time, location at the solar disk) according to the catalog. Based on this information we selected the solar flares with radio bursts according to RSTN data. There are 26 events in total. We reconstructed the spectrum for the temporal maximum of the radio burst using data of all available frequency range. For the events jointly observed by the NoRP, we combined the data from these instruments into one composite dynamic spectrum. The flux of gyrosynchrotron microwave emission monotonously increases with increasing frequency until peak frequency. After this frequency, the microwave flux starts to decrease. The shape of the radio spectra of all selected events was typical for gyrosynchrotron emission [Dulk, 1985].

We obtained the spectrum parameters by fitting using the procedure tp_fit, part of the OVSA Explorer software (see [Nita et al., 2004], for more detail) and added linear interpolation for low-frequency and high-frequency parts of the spectra. In order to choose the better parameters, we calculated the standard deviation for the fitted curves obtained by the different methods. For the next step of the analysis, we used the parameter (spectral indices and peak frequency) corresponding to the fit with a minimum deviation value.

For comparison, we used the ratio of the proton peak integral flux for energies above 10, 30, 60 MeV (the catalog presented in the paper [Papaioannou et al., 2016]). Namely, there are the ratio parameters for channels 10 MeV to 30 MeV and 10 MeV to 60 MeV.

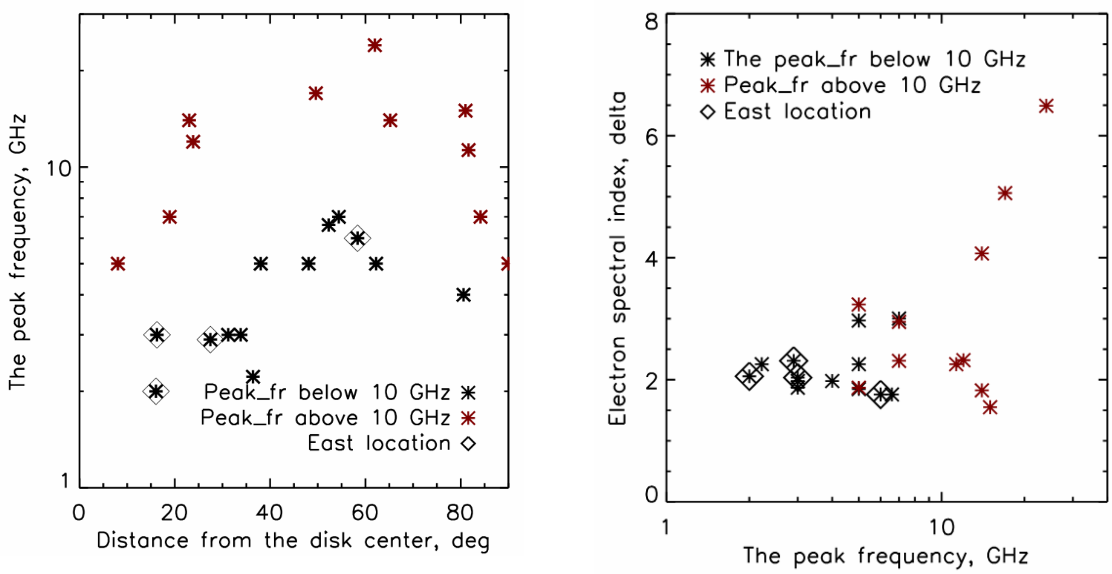
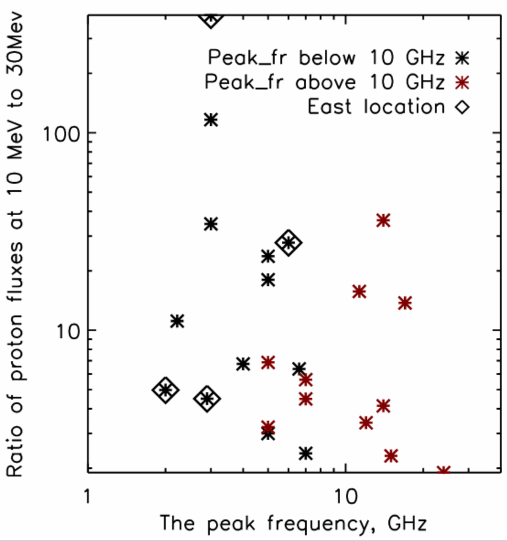


Fig. 1 The left panel: The peak frequency of the solar flares vs distance from the disk center. The black asterisks show the events with peak frequencies below 10 GHz and the red asterisk shows the events with peak frequencies above 10 GHz and the events related with them. The diamonds show the event located in the eastern part of the solar disk. The right panel: The electron spectral index relative to the peak frequency of the events.

Results

At first, we should check if there is any dependence between the peak frequency and location of the event on the solar disk. The left panel of Figure 1 presents the plot that shows the relationship between the peak frequency and position of the solar flare

.One can see two groups of events defined by the peak frequency value. The peak frequency of the first one is less than 10 GHz. It means that the magnetic field nearby the source of MW emission was not strong. The relationship between the peak frequency and distance from the solar disk center demonstrates the slow rise that reaches the maximum at about 60 degrees. We also revealed the other group of the events. For this group, the dependence of the peak frequency value relative to the event position looks similar to the first group. But the most of the frequency values are above 10 GHz. Both populations look like the branches located higher and lower in the plane of the peak frequency–distance. Such separation could mean that one group of events occurs in active regions with weak magnetic fields. The position of the other event group with the high value of the peak frequency was related with the large magnetic fields. We note that events located in the Eastern hemisphere all have peak frequencies below 10 GHz and blends with the corresponding dependence.



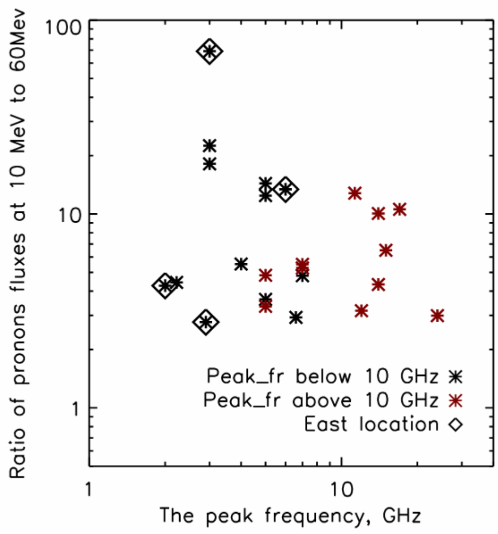


Fig. 2 The left panel: The ratio of the proton fluxes above 10 MeV to the proton fluxes above 30 MeV relative to the peak frequencies of MW spectra. The black asterisks show the events with peak frequencies below 10 GHz. The symbols as in Figure. 1The right panel: The ratio of the proton fluxes above 10 MeV to the proton fluxes above 60 MeV relative to the peak frequencies of MW spectra.

We marked the two groups by symbols of the different colors and tested if any other common properties are present for each group or not. The right panel of Figure 1 presents the relationship of the electron spectral index from the peak frequency. The electron spectral index δ is derived from the photon spectral index α by the formula $\delta=1.11\alpha+1.36$ [Dulk, 1985]. One can see that events with low peak frequencies are grouping nearby the electron spectral index about 2. This index is hard and assumes a large number of accelerated relativistic electrons with high energies and/or high level of processes of acceleration. The other group splits into two subsets with the opposite tendencies: of index hardening and of index softening. Most possibly these tendencies are related to the feature of magnetic field topology and they should be analyzed in details.

Figure 2 presents the proton flux ratio in two energy channels relative to the value of the peak frequencies of MW bursts corresponding to the events. The ratio is characteristic of spectral properties of the SEP proton flux. The higher values mean softer proton fluxes. We can see that both graphs look like the combination of the two distributions related to the peak frequencies above 10 GHz and below this value. Both distributions look like the normal distribution and have the maximum about 3 GHz and 15 GHz. We cannot claim anything definitive about the relation between the spectral properties of proton fluxes in SEP events and the peak frequency of the MW burst. But we propose that the peak frequency as a parameter splits SEP events into two populations. The properties and acceleration mechanisms of these populations should be different because of the same spectral characteristics of protons in SEPs achieved based on the different properties of the magnetic field in solar flares.

Summary

We carried out the comparative analysis of the spectral characteristics of SEP proton fluxes and the peak frequency of solar flare microwave spectra. We did the preliminary analysis dependence of the peak frequency from the distance from the center of the solar disk. The results show the existence of two populations of events related to high and low values of the peak frequency. We defined the border value as 10 GHz. These groups show the different properties as for electron spectral index and spectral properties of proton flux of SEPs.

Acknowledgment

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