About Productivity of the Solar Energetic Particle Events

Zhdanov D.A. [1], *Kashapova L.K.* [1], *Myshyakov I.I.* [1], *Miteva R.* [2]

[1] The Institute of Solar-Terrestrial Physics, SB RAS, Irkutsk, Russia
[2] Space Research and Technology Institute – Bulgarian Academy of Sciences, Sofia, Bulgaria
E-mail: zhdanov@iszf.irk.ru

Abstract.

We present an analysis of 22 SEPs events related to flares that demonstrate significant microwave emission. We analyzed the microwave burst parameters characterizing acceleration processes for each event. In some events, despite the significant microwave signatures, powerful SEPs were not produced.

The current study aimed to check the correlation of the SEP event productivity of active regions based on features of their magnetic field topology and the presence of type III radio bursts as an additional indicator of open magnetic field lines. The magnetic field during the pre-flare stage was extrapolated by a potential approximation. The obtained results are discussed.

Introduction

Solar energetic particles (SEPs) relate with one of the most important aspects of space weather. The electrons, protons and ions observed in situ on the terrestrial orbit present a real hazard to humans and technological devices. The problem of physical understanding of the processes of acceleration, escape and transport from the solar source to the particle detector has been still actual nowadays (see, for example, *Klein and Dalla,* 2017). There are no doubts that the solar origins of SEP events relate to solar flares and coronal mass ejections (CMEs), but the role distribution between these phenomena is unclear. One of the studied problems is on the indicators of acceleration processes. Emission generated by electrons could be directly observed both in X-rays and microwaves. However, the emission generated by protons is observed very rarely because of the low flux level of emission and the insufficient threshold of the current instruments. There are several approaches based on observational and theoretical studies. For example, *Chertok et al.* [2009] demonstrated the close relation of the SEP proton fluxes and properties of microwave non-thermal gyrosynchrotron emission. Also, it is not clear what the importance of particle acceleration is over their escape to interplanetary (IP) space.

The SEP events may not be related to powerful soft X-ray solar flares. But on the other hand, weak flares may be associated with prominent SEP events. In the work by *Bogomolov et al.* [2018] a comparison between the characteristics of two flares was carried out. These flares show very close characteristics of the acceleration processes. It is turned out that the flare related to the proton-rich SEP event took place in the active region where 3D reconstruction of magnetic field lines demonstrated the presence of a fan of high loops associated with open magnetic field lines. Moreover, the flare was associated with the type III radio burst that is also evidence of the presence of open magnetic field lines during the solar flare and nearby the flare location.

Based on these results we could make the assumption and show that one of the indicators of the existence of advanced possibilities for proton escaping could be the domination of open magnetic field lines in the active region producing the event. This hypothesis should be checked on a more statistically representative set of data. Microwave emission properties could be an indicator of the presence of acceleration process.

And the type III radio bursts will be an additional indicator of existing of open magnetic field lines nearby the flare location.

Data and analysis

We used the catalog of the SEP events detected by the Wind/EPACT instrument over the period 1996–2016 [*Miteva et al.* 2018]. Microwave data was obtained by the Badary Broadband Microwave Spectropolarimeter (BBMS) located in Radio Astrophysical Observatory of the Institute of Solar-Terrestrial Physics, Russia [*Zhdanov et al.* 2011].

We considered two groups of SEP events. The first group consisted of solar flares associated with proton events, the second group consisted of solar events without protons. Table 1 shows a list of 18 proton-rich events and 3 non-proton-rich events. We had described the microwave properties of the first group (№1-18) in *Zhdanov et al.* [2018].

The second group contains solar flares which had a radio flux higher than 500 sfu at two or more frequencies simultaneously in the range from 3.7 to 17 GHz, but were not followed by significantly enhancement in the proton flux. We used the Nobeyama radio polarimeter catalog of radio fields to find such events in the period 2010–2017. We chose only the events that were simultaneously observed by the BBMS also. Thus, we could found only 3 events (№19-21).

Table 1 List of SEP events with properties of the associated phenomena.

№	Date (yyyy-mm-dd)	Start time (UT)	GOES class	Radio $Flux_{max}$ at F_{max} (sfu)	Radio F_{max} (GHz)	Proton flux 28-72 MeV	Flare Position	CME Speed km/s	Magnetic configuration	type III radio bursts: Learmonth catalogue	type III radio bursts: Wind/ WAVES
5	2012-03-07	01:05	X1.3	7000	9,4	9.591/106851	N22E12	1825	closed	No	Yes
4	2012-01-23	03:38	M8.7	8000	4,0	9.455/196610	N28W21	2175	closed	No	Yes
6	2012-05-17	01:25	M5.1	600	5,0	1.357/1296	N11W76	1582	-	No	Yes
2	2011-06-07	06:16	M2.5	800	6,5	0.3390/7315	S21W54	1255	open-closed	No	Yes
3	2011-08-09	07:48	X6.9	2000	10,0	0.1270/284	N17W69	1610	open-closed	No	Yes
8	2013-05-15	01:25	X1.2	1600	7,0	0.0352/484	N12E64	1366	closed	No	Yes
11	2014-02-20	07:26	M3.0	500	6,0	0.0309/272	S15W73	948	open-closed	Yes	Yes
13	2015-06-18	00:33	M1.2	60	2,0	0.0252/296	S16W81	1714	-	No	Yes
14	2015-06-21	02:06	M2.6	1100	7,5	0.0203/266	N13E10	1366	closed	No	Yes
10	2013-11-02	04:40	C8.2	80	4,0	0.0142/326	S23W04	828	closed	No	Yes
15	2015-06-25	08:02	M7.9	4500	9,0	0.0142/1093	N09W42	1627	closed	No	Yes
9	2013-06-21	02:30	M2.9	110	4,7	0.0073/153	S16E73	1900	-	No	Yes
1	2011-02-15	01:44	X2.2	1000	8,0	0.0037/84	S20W10	669	closed	No	Yes
16	2016-03-16	06:34	C2.2	12	7,0	0.0024/14	N12W88	592	-	No	Yes
12	2014-12-17	04:25	M8.7	800	7,0	0.0016/107	S20E09	587	closed	Yes	Yes
17	2016-04-18	00:14	M6.7	350	6,0	0.0007/u	N12W62	1084	closed	No	Yes
7	2013-03-15	05:46	M1.1	120	1,5	0.0004/u	N11E12	1063	open-closed	No	Yes
18	2016-07-23	05:00	M7.6	700	7,0	0.0004/u	N05W73	835	-	No	Yes
19	2013-11-10	05:12	X1.0	550	8	-	S13W14	682	closed	No	Weak
20	2014-10-22	01:39	M8.7	1000	9,4	-	S12E21	no cme	closed	No	No
21	2015-03-10	03:21	M5.1	1100	17	-	S16E34	1040	open	No (V type)	Weak

The magnetic field was reconstructed using data, provided by Heliospheric and Magnetic Imager (HMI) [*Schou et al.* 2012] instrument onboard Solar Dynamics Observatory (SDO) spacecraft [*Pesnell et al.* 2012]. We reconstructed a coronal magnetic field in a potential approximation for the all events from two groups. The coronal magnetic field was calculated in a potential approximation using a method, based on Green's function approach.

The applied method works in a spherical geometry. Distribution of the radial magnetic component over the photosphere level, calculated from SDO/HMI vector magnetograms with resolved pi-ambiguity, is used as input boundary conditions. The height of the computational domain is 150 Mm that defines the maximum height of the reconstructed loops up to 0.2 solar radii. We considered force lines to have either a closed configuration or an open configuration. Table 1 shows the result of determining the magnetic field configuration for all events. The presence of the type III radio bursts we checked by two ways. We used the information from Learmonth radio spectrograph (25–180 MHz) catalogue of radio bursts (http://www.sws.bom.gov.au/World_Data_Centre/) by Automated Radio Burst Identification System (ARBIS 2) based on the algorithm by *Lobzin et al.* [2009]. Information about the presence of the burst at lower frequencies we obtained from the Wind/WAVES data.

Discussion and conclusion

Initially, we checked the presence of open magnetic field line configuration in active regions as factor that leads to more proton-rich event. However, we found the closed configuration of the magnetic field in most of the active regions associated with the solar origins of proton-rich SEP events. Figure 1 shows the open-closed magnetic field configuration in event SOL2012-01-23.

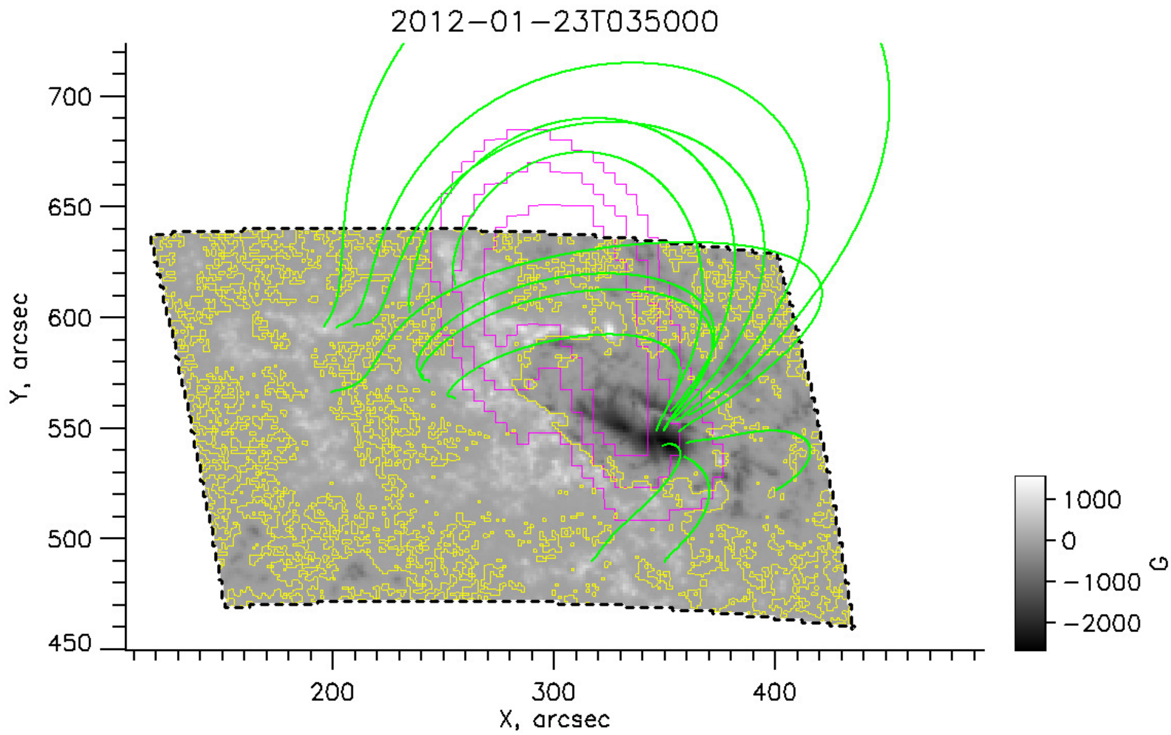

Fig. 1 Example of closed magnetic field configuration in the event SOL2012-01-23, green lines – force lines, purple contour – the 17 GHz radio source by Nobeyama Radioheliograph (NoRH). Contour levels – 0.7, 0.8, 0.9 from of the maximum.

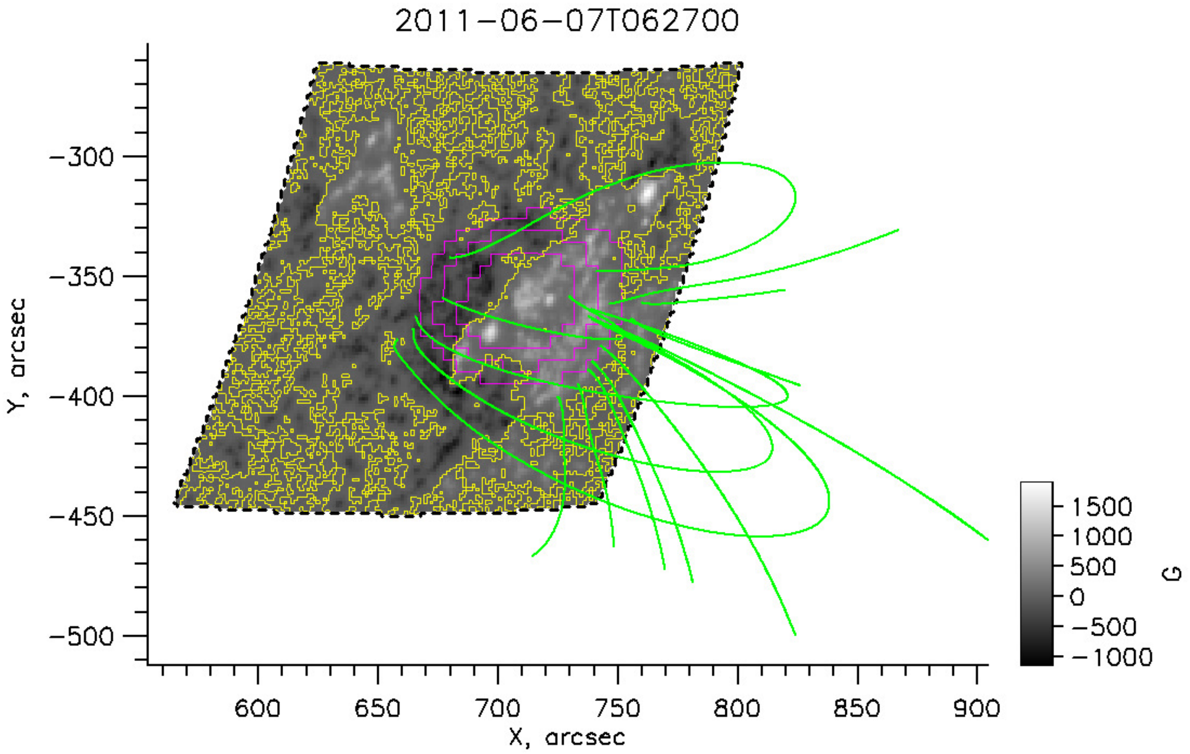

Fig. 2 Example of open-closed magnetic field configuration in the event SOL2011-06-07, green lines – force lines, purple contour – the 17 GHz radio source (NoRH). Contour levels – 0.7, 0.8, 0.9 from of the maximum.

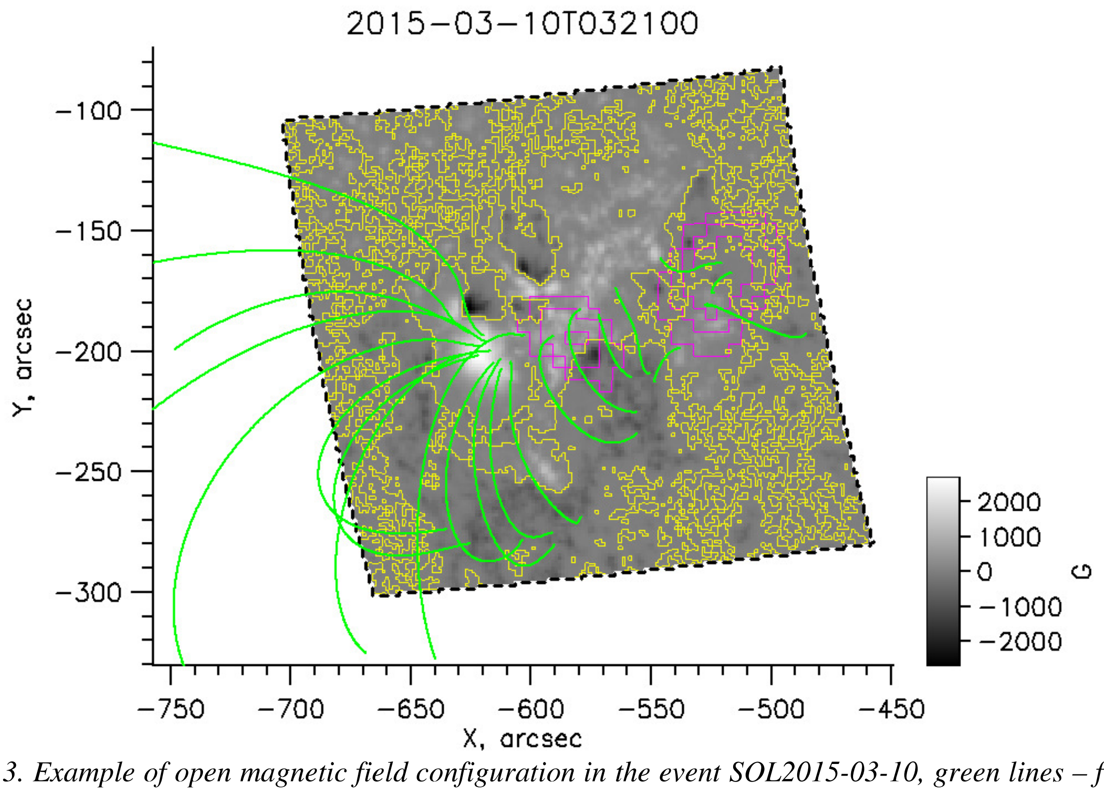

Fig. 3. Example of open magnetic field configuration in the event SOL2015-03-10, green lines – force lines, purple contour – the 17 GHz radio source (NoRH). Contour levels – 0.85, 0.9, 0.95 from of the maximum.

We did not find clear evidence of open magnetic configurations in the active regions related to the studied proton events. Conversely, some configurations look like an open-closed configuration. Figure 2 shows the open-closed magnetic field configuration in the active region where the event SOL2011-06-07 occurred. We found the open-closed configuration of the magnetic field in active regions associated with 4 proton events out of 17 only.

Only one flare was in active region where the magnetic field configuration was clearly open. But this flare is associated with unproductive proton events. Figure 3 shows the open magnetic field configuration in event SOL2015-03-10. But the catalogue of Learmonth spectrograph showed presence the type V during the corresponding flare. If the burst identification is correct, it means that accelerated electrons escaping from the solar atmosphere were captured by high closed magnetic field lines. The presence of the low-frequency type III bursts indicates open magnetic field lines extend from 0.5 solar radii into IP space [*Cane et al.* 2002]. Our method allowed reconstructing the magnetic field lines up to 0.2 solar radii. The presence of type V instead the type III could mean that the used approach for estimation is not working properly.

Moreover, we were faced with uncertainties with the detection of type III radio bursts. For most of the events where the Learmonth catalogue did not reveal the type III presence, the WIND/Waves observations showed the presence of type III at lower frequencies. The visual inspection of the Learmonth dynamic spectra also reveal type III-like activity at the time of interest. The events without proton fluxes demonstrated week evidence or absence of type III.

Thus, the approach taking into account the configuration of magnetic field lines in the active regions associated with the SEP event should be improved based on the results obtained in the current study.

Acknowledgement

This study is supported by the project 'The origin on solar energetic particles: Solar flares vs. coronal mass ejections', co-funded by the Russian Foundation for Basic Research with project No. 17-52-18050 and the National Science Fund of Bulgaria under contract No. DNTS/Russia 01/6 (23-Jun-2017). The results were obtained using the equipment of Center for Common Use «Angara» http://ckp-rf.ru/ckp/3056/. DZ and LK thank the budgetary funding of Basic Research program II.16 for partial support.

References

Bogomolov, A.V., Myagkova, I.N., Myshyakov, I., et al. (2018). Comparative analysis of the proton generation efficiency during 17 March 2003 and 11 April 2004 solar flares. J Atmospheric and Solar-Terrestrial Physics, 179, 517-526.

Cane, H.V., Erickson, W.C., Prestage, N.P., (2002). Solar flares, type III radio bursts, coronal mass ejections, and energetic particles. Journal of Geophysical Research (Space Physics) 107, 1315.

Chertok I.M., Grechnev V.V.,Meshalkina N.S.(2009) On the Correlation between Spectra of Solar Microwave Bursts and Proton Fluxes near the EarthAstronomy Reports, 2009, Vol. 53, No. 11, 1059–1069.

Klein, K.-L., Dalla S. (2017). Acceleration and Propagation of Solar Energetic Particles. Space Science Reviews, Volume 212, Issue 3-4, 1107-1136

Lobzin, V. V., I. H. Cairns, P. A. Robinson, G. Steward, and G. Patterson (2009), Automatic Recognition of Type III Solar Radio Bursts: Automated Radio Burst Identification System Method and First Observations, Space Weather, 7, S04002, doi: 10.1029/2008SW000425.

Miteva R., Samwel S. W., Costa-Duarte M. V. (2018), The Wind/EPACT Proton Event Catalog (1996 - 2016), Solar Physics, 293, no. 2, article id. 27, 44 pp.

Pesnell, W. D., Thompson, B. J., Chamberlin, P. C. (2012). The Solar Dynamics Observatory (SDO). Solar Physics, 275, no. 1-2, 3-15.

Reames D. V. (2015), What Are the Sources of Solar Energetic Particles? Element Abundances and Source Plasma Temperatures, Space Science Reviews, 194, no. 1-4, 303-327

Schou, J., Scherrer, P. H., Bush, R. I., et al. (2012). Design and Ground Calibration of the Helioseismic and Magnetic Imager (HMI) Instrument on the Solar Dynamics Observatory. Solar Physics, 275, no. 1-2, 229–259.

Zhdanov D.A., Zandanov V.G. (2011), Broadband microwave spectropolarimeters, Central European Astrophysical Bulletin, 35, 223-227.

Zhdanov, D., Kashapova, L.K., Miteva, R. (2018). Results of comparative analysis of the SEP events and the microwave bursts observed by 2-24 GHz and 4-8 GHz spectropolarimeters in 2010-2016. Tenth Workshop Solar Influences on the Magnetosphere, Ionosphere and Atmosphere», proceedings of the conference held 4-8 June, 2018 in Primorsko, 105-108.