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Some features of the sources of relativistic particles at the Sun in the solar cycles 21–23

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Abstract

Regularities of relativistic solar protons (RSP) generation and release from the Sun in the events of 21–23 solar cycles on data of neutron monitors, balloons and spacecraft have been studied. In all, 11 Ground Level Enhancements (GLE) of solar cosmic rays (SCR) were analyzed. The two-peak structure of solar proton intensity profiles gives certain evidence of that two distinct particle populations (components) exist: the early impulse-like intensity increase with a hard energy spectrum (prompt component, PC) and late gradual increase with a soft energy spectrum (delayed component, DC). The existence of two RSP populations is also confirmed by different forms of spectral fitting for PC and DC and by their dynamics as derived from neutron monitor data with optimization methods. It is shown that the PC energy spectrum has exponential form that may be an evidence of the acceleration by electric fields arising in the reconnecting current sheets in the corona. The DC energy spectrum may be fitted by a power-law function. Considering the timing of generation and release of two RSP components from the solar corona, the following scenario may be suggested. The prompt component of RSP is produced during initial energy release in a low-coronal magnetic null point. This process is linked with the H-alpha eruption, onset of CME and type II radio emission. The accelerated particles of PC leave the corona along open field lines with diverging geometry that results in strong focusing of a bunch. Particles of DC originally are trapped in magnetic arches in the low corona and accelerated by a stochastic mechanism at the MHD turbulence in expanding flare plasma. Accelerated particles of DC can be then carried out to the outer corona by an expanding CME. They are released into interplanetary space after the magnetic trap is destroyed giving rise to the source of accelerated particles that is extended in time and azimuth.

Keywords: Relativistic solar protons; Acceleration; Energetic spectrum; GLE; Modeling

1. Introduction

In this paper, based on the data of neutron monitors, balloons and spacecraft, we consider regularities of relativistic solar protons (RSP) generation and release from the Sun in the events of solar cycles 21–23. In all, eleven Ground Level Enhancements (GLE) of solar cosmic rays (SCR) were analyzed on the data of ground based neutron monitors (NM). The worldwide NM network may be considered as a united multidirectional solar proton spectrometer in the relativistic energy domain. With the modeling of the NM responses to an anisotropic solar proton flux and comparing them with observations the parameters of primary solar protons outside the magnetosphere can be obtained (e.g., Shea and Smart, 1982; Cramp et al., 1997a,b; Vashenyuk et al., 2003a). This kind of analysis requires

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the data of more than 25 NM stations, and it consists a few steps:

1. Definition of asymptotic viewing cones of the NM stations under study by the particle trajectory computations in a model magnetosphere (with a step in rigidity of 0.001 GV). The magnetosphere model by Tsyganenko (2002a,b) was employed.
2. Calculation of the NM responses at variable primary solar proton flux parameters.
3. Application of a least square procedure (optimization) for determining primary solar proton parameters (energy spectrum, anisotropy axis direction, pitch-angle distribution) outside the magnetosphere by comparison of computed NM responses with observations. In this paper, we will concentrate on the energy spectra of solar protons. The control of accuracy of the obtained spectra was carried out by summation of the measured responses of neutron monitors with a random quantity equal to a probable error of experimental data. The resulting dispersion of solar proton parameters calculated by the optimization procedure can serve a measure of an error of the given method. Such error estimation is given for all solar proton spectra under study (see below).

The validity criterion for the spectra obtained from the NM records may be provided by comparison with the direct solar proton intensities measured in adjacent energy intervals by balloons and spacecraft. At the same time, the direct solar proton data help to extend to lower energies the spectrum of solar protons obtained on data of neutron monitors that is limited from below, owing to the atmospheric cutoff, at about 450 MeV. The upper limit of SCR spectrum is defined by maximum energy of accelerated particles that for majority of GLEs does not exceed 10 GeV (e.g., Miroshnichenko, 2001).

Some of the GLEs considered in our paper have been already studied by modeling methods by different authors (Shea and Smart, 1982; Debrunner et al., 1988; Cramp et al., 1997a,b; Pchelkin et al., 2000; Vashenyuk et al., 2000; Klein et al., 2001; Duldig, 2001; Bieber et al., 2002). Comparison of their results with our findings shows, almost in all cases, close similarity of spectra, anisotropy axes and other parameters. At the same time, based on our analysis, we suggest the new interpretation of considered events in the framework of the hypothesis of two SCR populations (components) in relativistic energy range. These components can be presumably connected to various sources (mechanisms) of particle acceleration at/near the Sun.

2. Observations

A list of studied eleven GLEs of the solar cycles 21–23 is given in Table 1 where the event number, date, onset time of type II radio burst, importance and heliocoordinates of the flare are also indicated. The onset time of the type II radio emission corresponds to the start of energy release at the null magnetic point close to the low coronal level and related with its H-alpha eruption and start of CME (Manoharan and Kundu, 2003). The type II onset was also found to be a marker of relativistic proton acceleration (Cliver et al., 1982). In every event under study, we tried to reveal the prompt (PC) and delayed (DC) components of relativistic solar protons judging on their spectral form. The best fits for the PC spectra are provided by exponential forms $J = J_0 \exp(-E/E_0)$, where E_0 is characteristic proton energy. As to delayed component, its spectra may be fitted by the power-law forms $J = J_1E^{-\gamma}$.

The corresponding parameters of the PC and DC spectra are displayed in the last four columns of Table 1, where characteristic energies E_0 are given in GeV and proton intensities – in units of $m^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}$. In present work, spectra parameters in Table 1 were derived by these authors using the optimization procedure for all

Table 1
Parameters of energetic spectra of relativistic solar protons

No.	No. of GLE	Date	Type II radio onset	Flare importance	Heliocoordinates	PC spectrum (exponential)		DC spectrum (power-law)	
						J_0	E_0	J_1	γ
1	31	07.05.1978	03.27	1B/X2	N23W82	1.4×10^4	1.65	–	–
2	38	07.12.1982	23.44	1B/X2.8	S19W86	1.5×10^5	0.35	2×10^3	3.2
3	39	16.02.1984	08.58	–	-W132	–	–	1.6×10^4	6.2
4	42	29.09.1989	11.33	-/X9.8	-W105	1.6×10^4	1.85	2×10^3	4.2
5	43	19.10.1989	12.58	4B/X13	S27E10	7×10^3	0.65	4×10^4	4.5
6	44	22.10.1989	18.05	2B/X2.9	S27W31	1×10^5	0.62	5×10^3	4.2
7	59	14.07.2000	10.20	3B/X5.7	N22W07	1.1×10^4	0.68	2×10^4	5.6
8	60	15.04.2001	13.19	2B/X14.4	S20W85	2×10^5	0.48	2×10^3	5.1
9	65	28.10.2003	11.02	4B/X17.2	S16E08	1.5×10^5	0.49	3.5×10^3	3.5
10	67	2.11.2003	17.03	2B/X8.3	S14W56	1.5×10^3	0.78	8×10^3	6.0
11	69	20.01.2005	06.44	2B/X7.1	2B/X7.1	1.5×10^5	0.72	7.5×10^4	6.2

events, excepting for the GLE 43 (19 October 1989). This GLE consisted of a precursor short-lived pulse and the basic increase with a wide maximum. Shea et al. (1991) found that the spectrum of the precursor pulse was exponential in rigidity, and the basic increase (near the event maximum) had the power-law spectrum in the rigidity interval between 2 and 3 GV. In Table 1, we present the parameters of those spectra in energy units.

In their modeling study of the GLE of 7 May 1978, Shea and Smart (1982) have obtained a solar particle spectrum in conventional rigidity exponential form. Using our optimization method, we come to the conclusion that this spectrum in relativistic range may be described also by exponential function on energy (within the error limits), and the parameters of this revised spectrum are given in Table 1. As the event of 7 May 1978 was unique in the sense that it consisted of a very short-lived and anisotropic increase. And the spectrum during the whole event had an exponential form. Therefore it is possible that the whole event consisted of the prompt component only. So a column for DC in Table 1 is empty. The contrary situation was observed for the GLE of 16 February 1984. Despite the impulse-like intensity profile is characteristic for PC, the power-law spectrum and great time delay made us to account this to the DC type. Note that our estimations are similar to the values obtained in Debrunner et al. (1988).

2.1. Examples of modeling study

Figs. 1–4 demonstrate some results of our analysis by the example of events 7, 9–11, from Table 1 (GLEs Nos. 59, 65, 67, 69). The two-peak structure of solar proton intensity profiles as well as different character of energy spectra show presence of two distinct particle populations (components) – the prompt (PC) and delayed (DC) ones.

2.1.1. The "Bastille day" GLE 59 (14 July 2000)

This event was related to the solar flare of importance 3B/X5.7, with the heliocoordinates N22, W07. The type II radio emission started at 10:20 UT. Fig. 1(a) displays profiles of increase during the GLE of 14 July 2000 at the NM stations Thule and Goose Bay that accept the direct solar proton flux coming from the Sun. The vertical arrow indicates the onset time of II type radio emission, shifted back on 8 min. (supposed moment of relativistic particle generation on the Sun, see Cliver et al., 1982). The numbered arrows correspond to the moments of time when in the RSP flux dominates the prompt component (1) and delayed one (2). Fig. 1(b) and (c) show the derived by modeling technique spectra of PC (1) or DC (2) in double logarithmic and semi-logarithmic scale, respectively. In Fig. 1(b) and (c) are also presented the data of direct solar protons measured by GOES spacecraft and balloons launched at Apatity

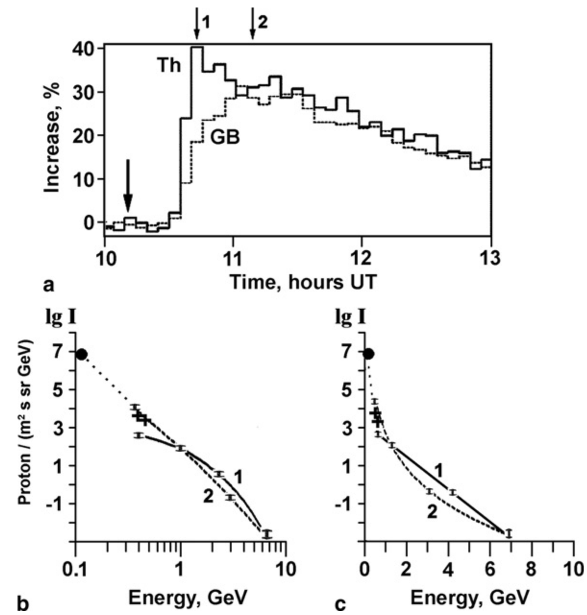

Fig. 1. "The Bastille Day" GLE of 14 July 2000. (a) Increase profiles at NM stations Thule (Th) and Goose Bay (GB). Vertical arrow marks a probable moment of particle generation at the Sun. Arrows 1 and 2 mark the moments of time when the energy spectra of RSP prompt component, PC (1) and delayed component, DC (2) were derived; those spectra are given in double logarithmic (b) and semi-logarithmic (c) scales. The data of direct solar proton measurements are shown by crosses (balloons) and blacked dots (GOES spacecrafts). Note an exponential form of the spectrum 1 (solid line) related to the prompt component and the power-law spectrum 2 (dashed line) related to the delayed component of relativistic solar protons.

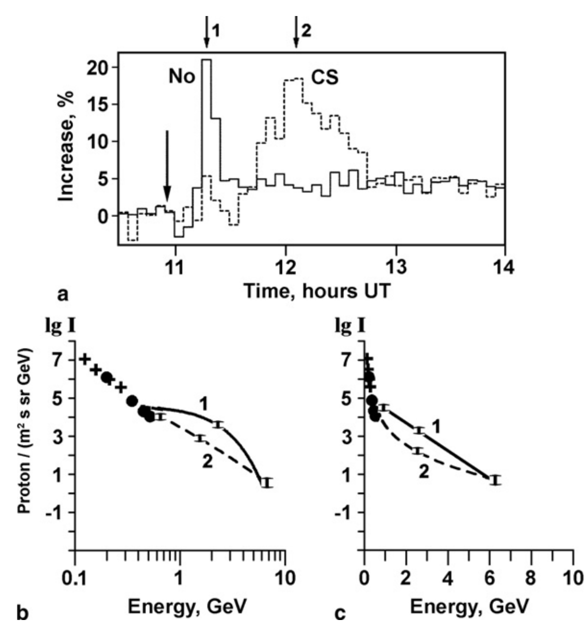

Fig. 2. Prompt and delayed RSP components in the GLE of 28 October 2003 (designations are the same as in Fig. 1): (a) intensity profiles at the NM stations Norilsk (No) and Cape Schmidt (CS); (b) and (c) derived energy spectra of PC (1, *solid line*) and DC (2, *dashed line*). Direct solar proton data are crosses (balloons) and blacked dots (GOES spacecraft).

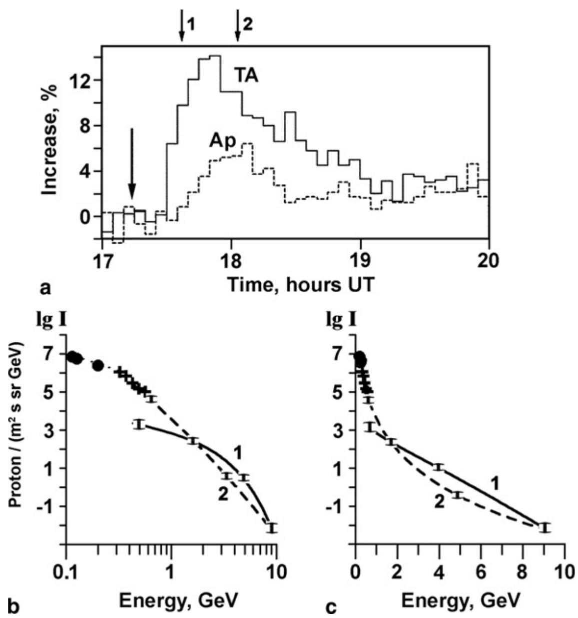

Fig. 3. Prompt and delayed components of relativistic protons in the GLE of 2 November 2003 (designations are the same as in Fig. 1): (a) intensity-time profiles at the NM stations Terre Adelie (TA) and Apatity (Ap); (b) and (c) derived energy spectra of PC (1, *solid line*) and DC (2, *dashed line*). Direct solar proton data are crosses (balloons) and blacked dots (GOES spacecraft).

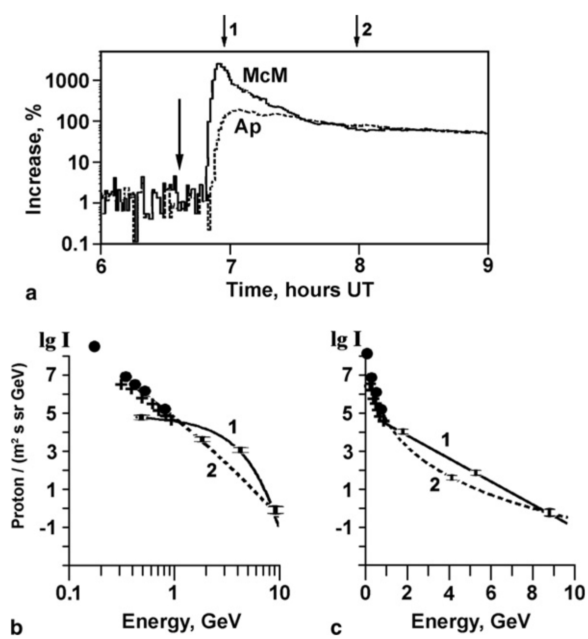

Fig. 4. Prompt and delayed components of relativistic protons in the GLE of 20 January 2005 (designations are the same as in Fig. 1): (a) intensity-time profiles at the NM stations McMurdo and Apatity (Ap); (b) and (c) derived energy spectra of PC (1, *solid line*) and DC (2, *dashed line*). Direct solar proton data are crosses (balloons) and blacked dots (GOES spacecraft).

(joint Lebedev Physical Institute (LPI) and Polar Geophysical Institute (PGI) balloon experiment, for details see Bazilevskaya and Svirzhevskaya, 1998).

As can be seen from Fig. 1(b) and (c), the PC spectrum would have an exponential dependence on energy (direct line in semi-logarithmic scale) and within the limits of shown error bars can be described by expression: $J = 1.1 \times 10^4 \exp(-E/0.68)$. The DC spectrum (2) depends on energy under the power law $J = 2 \times 10^4 E^{-5.6}$, and within the limits of error bars it is a direct line in double logarithmic scale. A good agreement is noticeable between a spectrum of DC obtained from the NM data and intensities of direct solar protons in adjacent interval of energy measured on balloons and GOES-8 spacecraft. Moreover, the spectrum of direct solar protons also depends on energy under the power law and appears to be an extension of DC spectrum of relativistic solar protons into the energy range from 700 to 100 MeV. Thus, the mechanism of generation of DC is effective enough in a wide energy range. As to the spectrum of PC, it is seen that in the range of 100 MeV the intensity of direct protons consistent with the PC spectrum should be 4 orders as low as the intensity of DC particles. In fact, the intensity of 100 MeV protons is at background level and they are inaccessible to direct measurements. At the same time, the spectrum of delayed component has extension with the same slope into the range of proton energies of 100–700 MeV covered with the data of direct measurements. The spectrum of prompt component has no extension into the range of moderate energies. Similar to this modeling study of the "Bastille day" GLE at 11:00 UT (Duldig, 2001) gave the power-law spectrum on rigidity, with an exponent about −7. This value will quite be coordinated to results of our calculations of DC energy spectrum where $\gamma = -5.6$ (Table 1).

2.1.2. The GLE of 28 October 2003

The GLE 65 of 28 October 2003 was related to the flare of 4B/X17.2 importance, with the heliocoordinates S16, E08. The type II radio onset was reported at 11:02 UT. Fig. 2(a)–(c) displays presence of two components of RSP in this event. Designations in Fig. 2 are the same as in the previous case. The increase profiles at Norilsk and Cape Schmidt stations are shown. The prompt component of RSP (1) is manifested itself by impulse-like increase at Norilsk neutron monitor and by the less expressed first of two peaks at Cape Schmidt station. The delayed component (2) has been distinctly registered only by the Cape Schmidt neutron monitor.

In Fig. 2(b) and (c), the derived spectra of prompt (1) and delayed (2) components are presented. We note that the PC spectrum (1), as well as in the previous case, is exponential in energy $J = 1.5 \times 10^5 \exp(-E/0.49)$, and the spectrum of DC (2) has a power-law form $J = 3.5 \times 10^3 E^{-3.5}$. This DC spectrum may be extended with the same slope into the moderate energy range of solar protons measured in the balloon and spacecraft experiments. As demonstrated by Perez-Peraza et al.

(2003), the DC spectrum could be produced by mechanism of stochastic acceleration due to interaction between Alfvén MHD mode turbulence and particles trapped in the low coronal magnetic arches. The extrapolated intensity of the prompt component (spectrum 1) at energy 100 MeV, however, is about 3 orders of magnitude lower than that for DC (spectrum 2), so it turned out to be at background level and inaccessible to direct measurements.

2.1.3. The GLE of 2 November 2003

The GLE 67 of 2 November 2003 was related to the solar flare of 2B/X8.3 importance, with the heliocoordinates S14, W56. The type II radio onset was reported at 17:03 UT. In Fig. 3(a), we show two intensity-time profiles as registered by the neutron monitors at the Terre Adelie (TA) and Apatity (AP) stations. It is noticeable that the TA profile seems to be a superposition of the prompt and delayed components, while the Apatity NM registered mainly the delayed component. Numbered arrows 1 and 2 mark the moments of definition of the spectra shown in Fig. 3(b) and (c). As in the previous two cases, one can see again that the PC spectrum measured early in the event has exponential dependence on energy, while that of DC is power-law one. As against the previous cases, in the given event a bending of solar proton spectrum is evidently observed, as follows from direct measurements in the range of 100–350 MeV (Fig. 3(b)).

2.1.4. The GLE of 20 January, 2005

The super GLE 69 occurred on 20 January 2005 and was the greatest event since 23 February, 1956. The parent solar flare 2B/X7.1 has heliocoordinates N14, W61. The type II radio onset was reported at 06:44 UT. The GLE was extremely anisotropic. Fig. 4(a) shows intensity-time profiles as registered by the neutron monitors at Mc Murdo (McM) and Apatity (AP) stations. The increase at McMurdo was about 2300% that exceeded 20 times the appropriate effect on the NM Apatity, which, in turn was significant (~100 %). As in preceding cases we can see the presence of the prompt (1) and delayed (2) components. Corresponding spectra of PC (1) and DC (2) are shown in Fig. 4(b) and (c). The spectrum of PC is exponential in energy: $J = 1.5 \times 10^5 \exp(-E/0.0.72)$, and the spectrum of DC has a power-law form: $J = 7.5 \times 10^4 E^{-6.2}$. As in the previous cases the good consent of derived spectra with the data of direct solar proton measurements is observed.

3. Discussion and conclusions

The results of modeling study of 11 large GLEs of 21–23 solar cycles clearly show existence of two distinct populations of relativistic solar protons: prompt (PC) and delayed (DC) components. Due to large interplanetary transport length and its weak rigidity dependence (Bieber et al., 1994), formation of PC and DC hardly can be attributed on the account only interplanetary propagation effects since they have strongly different spectra.

One of important results is that the PC spectrum proved to have exponential form in energy, and this may be evidence of acceleration by electric fields arising in the reconnecting coronal sheets (e.g., Bulanov and Sasorov, 1975; Perez-Peraza et al., 1992; Vashenyuk et al., 2003). At impulsive magnetic reconnection in a current sheet an electric field arises which is directed along a null magnetic field line. The particles of surrounding plasma move along this electric field and gain energy, which is proportional to a path traveled in the electric field. At the same time, the number of particles traveled a given path in reconnecting area falls exponentially with increase of this path because of losses owing to a leaving of particles the acceleration volume due to drifts. So, the spectrum of particles accelerated by an electric field inside a volume, where reconnection proceeds should have exponential dependence on energy. The described here qualitative picture proves to be true by modeling computations, in which the structure of magnetic and electric fields in a reconnecting current sheet was reproduced (Vashenyuk et al., 2003b). The trajectories of particles of plasma accelerated in an electric field were computed and their energy was fixed at leaving the acceleration volume. The resulting spectrum of the accelerated particles had expressed exponential dependence on energy, that confirms a hypothesis about a magnetic reconnection as a source of prompt component of RSP.

The interplanetary propagation should not appreciably deform a spectrum of RSP, at least for the prompt component (PC). Rapid intensity increase and strong anisotropy, peculiar to the particles of the PC, testify to propagation in the IMF with the minimal scattering. Thus, the time of direct flight along an IMF line with characteristic length of 1.2 AU makes for particles with energy about 0.5 and 10 GeV of 13.2 and 10 min, respectively (note that corresponding ratios $v/c = 0.76$ and 0.996, where v is a particle velocity and c is a speed of light). Hence, relativistic solar protons in the energy range of 0.5–10 GeV come to the Earth within 3-min interval. In modeling technique (Vashenyuk et al., 2003), the 5-min averages of the NM data are used, therefore, obtained solar proton spectrum is suggested to be close under the form to a generation spectrum at the Sun, if only the particles were released simultaneously. The best fit for DC spectrum is a power-law dependence on energy with rather steep slope ($\gamma \sim$ 5–6). As a source of DC it would be possible to assume a coronal shock wave (Kahler, 1994). Acceleration on a shock wave also gives a power-law spectrum, but at nonrelativistic energy domain (Ellison and Ramaty, 1985). Being based on our earlier results, we are more inclined to consider acceleration by MHD turbulence as a probable mechanism for DC formation during explosive energy release in a flare (Miroshnichenko et al., 1996). The proton spectrum in such a case has a variable slope and should be described by a curve such as Bessel functions in rigidity in general case and by the power law in the high-energy limits (Gallegos-Cruz and Perez-Peraza, 1995). Our experimentally obtained spectra of DC of relativistic solar protons obviously correspond to this theoretical result. Therefore, considering the timing of generation and release of two relativistic proton components: PC and DC from the solar corona, a following scenario may be suggested. The prompt component of RSP is produced during initial energy release in a low-coronal magnetic null point. This process is linked with the H-alpha eruption, onset of CME and type II radio emission. The accelerated particles of PC leave the corona along open field lines with diverging geometry that results in high anisotropy due to strong focusing of a particle bunch. The DC particles are trapped originally in magnetic arches in the low corona. As the disturbance grows, DC particles are accelerated by a stochastic mechanism at the MHD turbulence in expanding flare plasma. Accelerated particles can be then carried out to the outer corona by an expanding (lifting) CME. They are released into interplanetary space after the magnetic trap is destroyed giving rise to an extended in time and azimuth particle source.

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