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SOLAR COSMIC RAY PROPAGATION MODEL FOR THE 28 OCTOBER 2003 GLE

E.V. Vashenyuk, Yu.V. Balabin, B.B. Gvozdevsky (*Polar Geophysical Institute, Apatity, Murmansk region 184 209, Russia*)
L.I. Miroshnichenko (*IZMIRAN, Troitsk, Moscow region, 142 190, Russia*)
K.-L. Klein, G. Trottet, and P. Lantos (*Observatoire de Paris, LESIA, CNRS-UMR 8609, 92195 Meudon, France*)

Abstract. A ground level solar particle event on October 28, 2003, related to a not well-connected flare 4B/X17.2, S16, E08, possessed a number of unusual features in the distribution of increase effect over the globe. From neutron monitor data by the least square technique, the parameters of relativistic solar protons (RSP) were obtained and their dynamics in the course of GLE studied. Among the RSPs two populations could be clearly distinguished: the prompt RSPs and the delayed ones. The prompt solar protons caused an impulse-like increase at several neutron monitor stations looking perpendicularly to the mean IMF direction. The delayed solar protons caused a slow intensity rise and arrived at the Earth from the antisunward direction (looking along the IMF). We argue that the high-energy solar protons came to the Earth along the loop-like IMF field line, connecting the Earth with the eastern flare on the Sun. Such IMF structure seems to be formed by a CME of a preceding flare 3B/X 1.2 on October 26.

1. Introduction

The particle event of 28 October 2003 was related to a solar flare 4B/X17.2, that occurred in the active region NOAA 10486 slightly to the east of the central meridian (S16, E08), nominally not well-connected with the Earth. In this paper we study the features of energetic solar proton and electron generation and propagation to the Earth based on the data of ground based neutron monitors and metric-to-kilometric radio emission from the electrons accelerated near the main radio onset observed in a wide wavelength range. The energy spectra along with the directional characteristics of relativistic solar protons derived from the data of neutron monitors can reveal possible sources of the accelerated particles on the Sun. The SPE of 28 October 2003 occurred when the interplanetary background was disturbed by an interplanetary CME (ICME), (SSC was registered at 01.31 UT) from a solar flare on 26 October. A corotating high-speed solar wind stream from a coronal hole started to the Earth at about 7 UT, a few hours before the GLE onset. This paper clarifies some aspects of the analysis of the event earlier performed by Miroshnichenko et al. (2005).

2. Neutron monitor observations and modeling results

By modeling the NM responses to an anisotropic solar proton flux and comparing those with the observations, the parameters of primary solar protons can be derived by the least square technique (Vashenyuk et al., 2003). Thus the parameters of modified power rigidity spectrum with variable slope $J_{||}(R) = J_0 R^{-\gamma^*}$, are J_0 the normalized constant, and $\gamma^* = \gamma + \Delta\gamma\cdot(R-1)$, where γ is the power-law spectral exponent at R = 1 GV, $\Delta\gamma$ is the rate of γ increase per 1 GV. The other parameters are the coordinates Φ and Λ defining anisotropy axis direction in the GSE system and the parameter C characterizing the pitch-angle distribution in the form of a Gaussian: $F(\theta(R)) \sim exp(-\theta^2/C)$. That is, 6 parameters are to be determined: J_0, γ, $\Delta\gamma$, C, Λ, Φ [3,4]. For a very complicated event of 28.10.2003 we had to use a model with two quite independent particle fluxes. Accordingly, the number of parameters in this model grew up to 12. In Table 1 the parameters of these two fluxes are presented for 6 times. Thus the dynamics of RSP in the course of the GLE can be traced. Fig.1 shows increase profiles at the NM stations of Norilsk, Cape Schmidt, Apatity and Barentsburg (Spitsbergen). The numbered arrows are the specified moments 1-7 of model calculations (Table 1). The peculiarity here is the impulse-like increase at Norilsk station (the prompt component of RSP), in contrast to the gradual increase at Mc Murdo (delayed RSP component). It can be seen that McMurdo station, which registered the maximum increase, accepted radiation from the antisunward direction. Both Apatity and Barentsburg stations, which were turned by their asymptotic cones nearly along the Parker spiral, showed a very little increase [1]. Dynamical changes in the pitch angle distribution (PAD) of the prompt component (PC) of RSP (initial pulse of intensity) are demonstrated in Fig.1 b (moments 1-3). The peculiarity here is that the maximum intensity of the PC was due to the particle flux from the direction nearly perpendicular to the mean IMF and to the symmetry axis of RSP. Also, Fig.1c shows the PAD evolution during the main intensity increase dominated by the delayed component (instants 5-7). In this time period all particles arrived approximately along the IMF but from the antisunward direction. Near the peak of the main increase (instant 7) the PAD becomes broader and additional flux appears from the direction of the Parker spiral.

Table 1. Energy spectra, pitch-angle distributions and apparent viewing directions of two RSP sources

№	Time	Flux1						Flux 2					
	UT	γ1	Δγ1	C1	θ1	Φ 1	$J1_0$	γ2	Δγ2	C2	θ2	Φ2	$J2_0$
1	11:25	0.63	-0.16	0.40	-57	-100	80	2.2	-0.31	0.17	1	135	7900
2	11:30	1.15	-0.24	0.42	-61	-107	920	1.2	-0.6	0.17	-2	144	4400
3	11:35	2.0	-0.16	0.40	-60	-105	2200	1.2	-0.7	0.15	-5	144	3000
4	11:40	0.84	-0.91	0.28	-60	-104	2970	0.8	-0.2	10.27	60	76	247
5	11:50	4.39	0.0	0.24	-59	-107	33100	1.5	-0.42	7.41	59	73	3600
6	11:55	3.93	0.0	0.23	-63	-100	22200	0.72	-0.38	11.82	63	80	1450
7	12:10	4.38	0.0	0.44	-62	-125	33300	5.60	-0.01	5.36	62	55	56400

The dynamics of the derived spectra are shown in double logarithmic (d) and semi logarithmic (e) scales. Spectra derived for instants 1-4 obviously correspond to the prompt component (PC) and are approximated by the dashed curve in Fig. 1 d, e. The spectra derived for instants 5-7 correspond to the delayed component (DC) of RSP. We note that within the estimated error limits the spectrum of PC can be approximated by an exponential function in energy: $J = 1.5 \cdot 10^5 \exp(-E/0.4)$ $m^{-2}s^{-1}st^{-1}MeV^{-1}$ (Balabin et al., 2005). During the maximum of the main increase (moments 5-7), the spectrum exhibits a power law in energy: $J = 3.5 \cdot 10^3 E^{-3.5}$ $m^{-2}s^{-1}st^{-1}MeV^{-1}$. The direct solar proton fluxes obtained by GOES-11 spacecraft and balloons launched in Apatity (Joint Lebedev Physical Institute and Polar Geophysical Institute balloon experiment (Bazilevskaya and Svirzhevskaya, 1998) are in good agreement with the derived spectra.

3. Discussion and conclusions

Based on neutron monitor modeling results presented above, and authors' analysis with using a great complex of data, including solar radioemission, spacecraft particle and radiowave data [Miroshnichenko et al., 2005], energetic particle dynamics can be sketched as shown in Fig.2. Early on 28 October 2003, the ICME related to the solar flare on October 26, reached the Earth. Soon after that, a high-speed solar wind stream has commenced. Thus at the GLE onset, the Earth was in the boundary region between a CME ejecta and corotating stream (CS). By means of the looped IMF inside the ejecta, the Earth was connected to the flare site in the eastern part of the solar disc. The high-energy solar protons (HEP) could come to the Earth along the loop-like IMF from the antisunward direction.

A similar view, that on January 20, 2005 GLE relativistic solar protons, which arrived at the Earth from the antisunward direction, propagated along the IMF magnetic loop was put forward in (Bieber et al., 2005). At the same time, the subrelativistic electrons, arrived at the Earth from the source in the western part of the solar disk along the Parker spiral IMF line, connected with a corotating stream (Miroshnichenko et al., 2005). The weak delayed flux of RSP along the Parker spiral direction could be explained by the effects of coronal propagation. Fig.2 b shows the spatial structure of the IMF near the Earth during the 28 Oct 2003 GLE reconstructed with using IMF and solar wind data. The dotted lines are the IMF field lines and arrows are average directions of relativistic proton flux registered by neutron monitors in Mc Murdo (McM) and Norilsk (No). An essential detail here is a sharp kink of the magnetic field with the curvature radius of $3 \cdot 10^6$ km, comparable with the Larmor radii of relativistic solar protons. We performed trajectory computations in the magnetic structure shown in Fig. 2 b. The RSP of the prompt component with small pitch-angles considerably deviated at the IMF kink. On the contrary, the particles with large pitch angles are little scattered on the kink and pass through it keeping the direction of movement along the magnetic field. This can explain the observed effect, namely, that the strongly anisotropic particle bunch of prompt solar protons, that was registered by neutron monitor at Norilsk and other stations with their asymptotic cones, was oriented nearly perpendicular to the IMF. The particles of the delayed component, mostly having large pitch-angles, little scattered on the kink of the IMF. Thus, the McMurdo station, looking nearly along the IMF, registered a delayed RSP coming along the IMF from the antisunward direction.

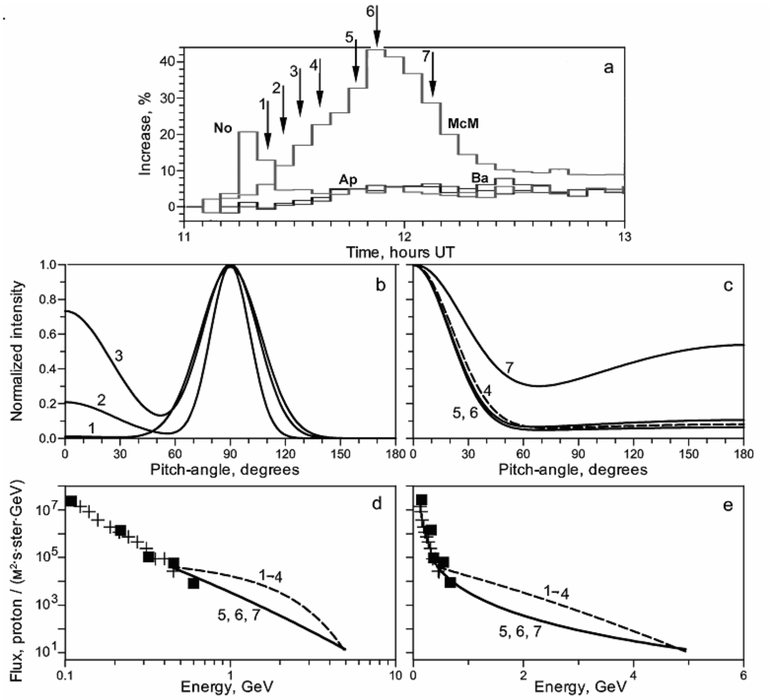

Fig. 1. Relativistic solar proton dynamics in the GLE of 28.10.2003. **(a)** increase profiles at Norilsk (No) and McMurdo (McM), Apatity (Ap) and Barentsburg (Ba) neutron monitor stations. Numbered arrows are the times, for which the parameters of RSP were derived (Table1). Dynamics of derived pitch angle distribution: **(b)** during the initial impulsive increase; **(c)** during the main intensity maximum. Dynamics of derived energetic spectra: (**d**) in double logarithmic scale, **(e)** in semi-logarithmic scale. Direct solar proton data are: crosses (balloons) and blackened squares (GOES-11 spacecraft).

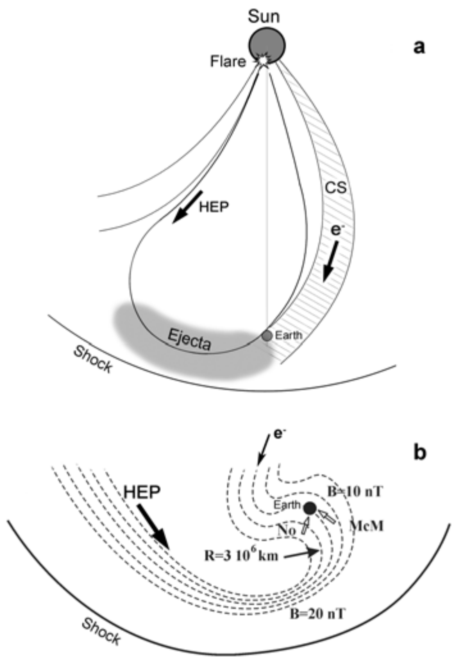

Fig. 2. **a.** The proposed model for the IMF structure during the 28 October, 2003 SPE. The Earth is at the boundary area between the ejecta from the flare of October 26 and corotating stream (CS) commenced to the Earth shortly before the event. By means of the looped IMF structure inside the ejecta, the Earth is connected to the flare site in the eastern part of the solar disc. High energy solar protons (HEP) come to the Earth from the antisunward direction. At the same time, the subrelativistic electrons can arrive at the Earth from a source in the western part of the solar disk along the Parker spiral IMF line, connected with a corotating stream.
b. The spatial structure of the IMF near the Earth during the 28 Oct 2003 GLE, reconstructed using IMF and solar wind data. The dotted lines are the IMF field lines and arrows are average directions of relativistic proton flux registered by neutron monitors in Mc Murdo (McM) and Norilsk (No). An essential detail here is a sharp kink of

the magnetic field with the radius of curvature $3 \cdot 10^6$ km, which is comparable with the Larmor radii of relativistic solar protons.

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