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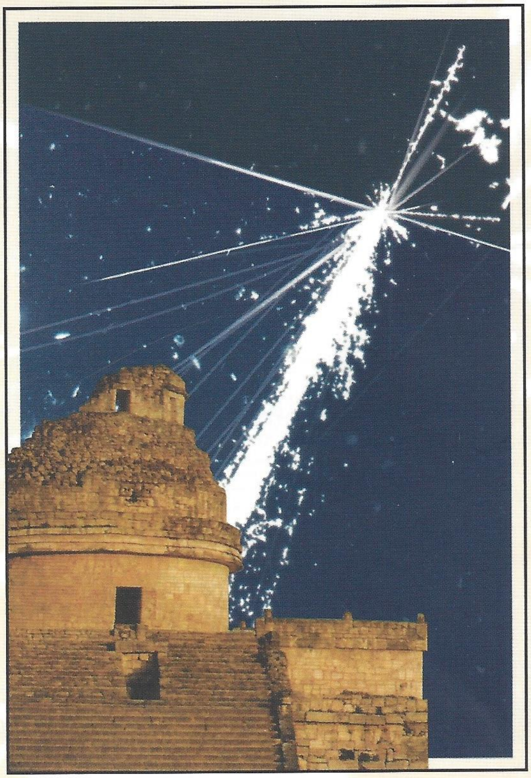

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Relativistic solar cosmic ray events (1956-2006) from GLE modeling studies

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Abstract: The modeling analysis of 14 large GLEs occurred in the period 1956-2006 on the data of the worldwide neutron monitors has been performed. In all studied cases two distinct RSP populations (components) were revealed: the early impulse-like intensity increase with exponential energy spectrum (prompt component), and the late gradual increase with a softer energy spectrum of the power law form (delayed component). The exponential spectrum may be an evidence of the acceleration by electric fields arising in the reconnecting current sheets in the corona. The possible source of delayed component particles can be stochastic acceleration at the MHD turbulence in expanding flare plasma.

Introduction

In this paper, based on the data of neutron monitors we consider regularities of relativistic solar protons (RSP) generation and release from the Sun in the 14 large Ground Level Enhancements (GLE) events occurring in the period 1956-2006. 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 [1, 2]. In this study we have carried out the analysis of 14 SCR events at ground level. One of the basic results of this study was the detection of two distinct populations (components) of relativistic solar cosmic rays: prompt (PC) and delayed (DC) ones. The PC and DC have various spectra and anisotropy characteristics and, probably various sources on the Sun.

Modeling technique of the GLE

Using the data of ground based neutron monitor network the parameters of primary solar protons outside magnetosphere can be obtained by a modeling [1, 2]. Our recent modeling technique, in general, is similar to that of [2], as it takes into account the contribution in the neutron monitor response not only vertical, but also oblique incident particles. This kind of analysis requires the data of no less than 20-25 ground-based cosmic ray stations, and consists of a few steps:

1. Definition of asymptotic viewing cones of the NM stations under study by the particle trajectory computations in a model magnetosphere.
2. Calculation of the NM responses at variable primary solar proton flux parameters.
3. Deriving with a least square procedure solar proton parameters (namely, energy spectrum, anisotropy axis direction, pitch-angle distribution) outside the magnetosphere by comparison of computed ground based detector responses with observations.

Determination of asymptotic viewing cones of NM stations under study was carried out by computations of the particle trajectories in the magnetosphere model Tsyganenko2001 [3] with a step in rigidity of 0.001 GV. For each given value of rigidity we calculated nine trajectories of particles that were "launched" in vertical, as well as in inclined directions under the angle of 20o in eight equally spaced azimuths. The response function of a given neutron monitor to anisotropic flux of solar protons is given by the relation:

$$\left(\frac{\Delta N}{N}\right)_j = \frac{1}{8}\sum_{i=1}^{8}\left(\sum_{R=1}^{20} J_{||}(R)\, S(R)\, F(\theta_{j,i}(R))\, A(R)\, \Delta R\right)$$

where $(\Delta N/N)_j$ is a percentage increase in the count rate N_j at a given NM station *j,* a modified power rigidity spectrum with variable slope $J_{||}(R)=J_0R^{-\gamma^*}$, $\gamma^*=\gamma+\Delta\gamma(R-1)$, J_0 is a normalization constant, γ is a power-law spectral exponent at R=1 GV, Δγ is a rate of γ increase per 1 GV [2]. The other parameters are the coordinates Φ and Λ, defining anisotropy axis direction in the GSE system; and a parameter C, characterizing the pitch-angle distribution (PAD) in form of a Gaussian: $F(\theta(R)) \sim exp(-\theta^2/C)$. $S(R)$ – is specific yield function (Debrunner et al., 1984, unpublished manuscript) and $\theta(R)$ – a pitch angle for a given particle. $A(R)$=1 for allowed and 0 for forbidden trajectories. So, 6 parameters are to be determined: J_0,, γ, Δγ, *C*, Λ, Φ.

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.

Some of the GLEs considered in our paper have been already studied by modeling methods by different authors e.g. [1,2,4,5], and many others. Comparison of their results with our findings shows, almost in all cases, close similarity of spectra and other parameters of RSP.

Results of GLE modeling studies

A list of studied 14 large GLEs occurred during the period 1956-2006 is given in Table 1 where the event number, date, onset time of type II radio burst (the start of CME [6] and marker of relativistic proton acceleration [7]), importance and heliocoordinates of the flare are also indicated. 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 = JO exp(-E/EO) where EO is characteristic proton energy. As to delayed component, its spectra may be fitted by the power-law forms J = J1 E-γ.The corresponding parameters of the PC and DC spectra are displayed in the last four columns of the Table where characteristic energies E0 are given in GeV and proton intensities - in units of m-2s-1sr-1 GeV-1.

Examples of modeling study

The GLE of 28 October 2003.

The GLE 65 of 28 October 2003 was related to the 4B/X17.2 flare, with heliocoordinates S16, E08, and the type II radio onset at 11:02 UT. Figure 1(a-c) displays presence of two components of RSP in this event [8,9,10]. The maxima at increase profiles at Norilsk (1) and Cape Schmidt (2) manifest itself the prompt (PC) and

Table 1: Energetic spectra parameters of relativistic solar protons

No	No of GLE	Date	Type II radio onset	Flare importance	Helio-coordinates	PC spectrum (exponential)		PC spectrum (power-law)	
						J0	E0	J1	γ
1	05	23.02.195	03:31	3B	N23W80	1.4·10	1.30	4.2·106	5.2
2	31	07.05.197	03:27	1B/X2	N23W82	5.6·10	0.71	1.2·104	4.1
3	38	07.12.198	23:44	1B/X2.8	S19W86	5.7·10	0.65	7.2·103	4.5
4	39	16.02.198	08:58	-	-W132	-	-	5.2·104	5.9
5	42	29.09.198	11:33	-/X9.8	-W105	1.9·10	1.54	3.5·104	4.1
6	44	22.10.198	18:05	2B/X2.9	SN27W31	7.5·10	0.87	1.5·104	6.1
7	47	21.05.199	22:19	2B/X5.5	N35W36	6.3·10	0.83	2.7·103	4.1
8	55	06.11.199	11:55	2B/X9.4	S18W63	7.3·10	1.20	5.0·103	4.3
9	59	14.07.200	10:20	3B/X5.7	N22W07	3.3·10	0.35	2.0·104	6.4
10	60	15.04.200	13:19	2B/X14.4	S20W85	1.3·10	0.53	3.5·104	5.3
11	65	28.10.200	11:02	4B/X17.2	S16E08	1.4·10	0.59	1.5·104	4.4
12	67	02.11.200	17:03	2B/X8.3	S14W56	5.6·10	0.33	2.7·103	6.6
13	69	20.01.200	06:44	2B/X7.1	N14W61	2.5·10	0.49	7.2·104	5.6
14	70	13.12.200	02:26	2B/X3.4	S06W24	1.1·10	0.33	4.4·104	5.5

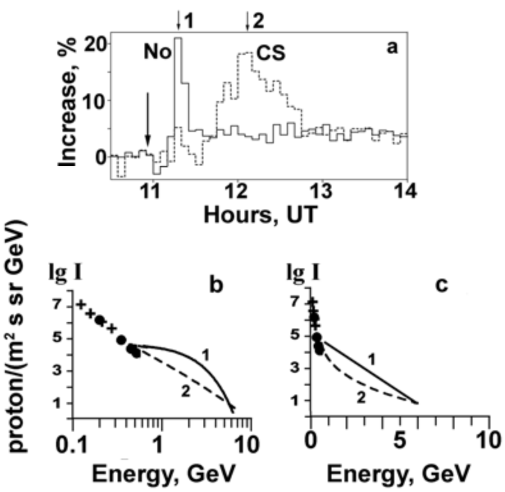

Fig. 1. Prompt and delayed RSP components in the GLE 28.10.2003. (a) intensity profiles at the NM stations: Norilsk (No) and Cape Schmidt (CS). (b, c) derived energy spectra of PC (1, solid line) and DC (2, dashed line) in the double logarithmic (c) and semilogarithmic scales respectively.

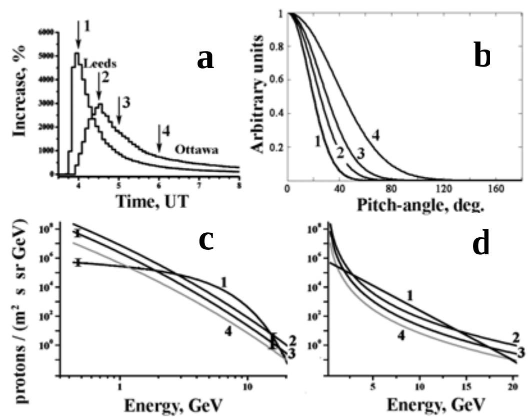

Fig. 2. Dynamics of relativistic solar proton flux in the GLE05: (a) - intensity-time profiles on the Leeds and Ottawa neutron monitors demonstrating the prompt and delayed components of RSP; (b) - derived pitch-angle distributions; (c) and (d) - energy spectra of relativistic solar protons in the double- and semi-logarithmic scales, respectively. Numbers near the curves correspond to the moments of time (UT): 1 - 04:00; 2 - 04:30; 3 - 05:00; 4 – 05:30; 5 – 06:00.

delayed (DC) components of RSP. In Figures 2b-2c the derived spectra of prompt (1) and delayed (2) components are shown.

We note that the PC spectrum (1), is exponential in energy $J = 1.4\times10^4 \exp(-E/0.59)$, and the spectrum of DC (2) has a power-law form $J = 1.5\times10^4 E^{-4.4}$ (see the Table). 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 [11], the DC power law spectrum could be produced by a mechanism of stochastic acceleration due to interaction between Alfvén MHD mode turbulence and particles trapped in the low coronal magnetic arches.

The GLE of 23 February 1956

The GLE of 23 February 1956 (or GLE05), largest for the entire 65-year history of SCR observations was caused by a giant solar flare (3+ or 3B) that occurred at 03:31 UT in the active region with heliocoordinates 25°N, 85°W. The 3.3 GHz radio burst was registered at 03:34 UT.

Since 50th many papers were devoted to the comprehensive study of this outstanding event. Note relatively recent modeling studies of the GLE 23.02.1956 [4,5,9]. We tried to do the modeling study of the GLE05 with the help of modeling technique described above.

In Figure 2 we present the dynamics of relativistic solar proton flux in the course of the GLE05 as it was derived by above modeling techniques in successive moments of time shown by arrows. Fig. 2a shows a profile of a huge prompt increase at the European NM station Leeds (manifestation of the PC) in comparison with a gradual enhancement at the North American station Ottawa (DC). The pitch-angle distribution shown in Figure 3b is rather narrow at the early phase of the event and widens with time. The derived energy spectra for four consecutive moments of time (1-4) are presented in Figures 2c, d in double-logarithmic and semi-logarithmic scales, respectively. From comparison of Fig. 2c and 2d, one can see that the spectrum 1 derived for the early phase of the event is exponential in energy: $J=1.4\times10^6\exp(-E/1.3)$, and the spectrum of DC (2) has a power-law form: $J= 4.2\times10^6 E^{-5.2}$ (04:00 UT).

Concluding remarks

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 [8,12,13].

Considering the timing of generation and release of two RSP components from the solar corona, as well as the specificity of their energetic spectra the following scenario may be suggested [10]. 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 [6]. 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. Two populations of SEP of moderate energies (>20 MeV) were identified also in [14]. One of them was related to a flare (soft X-rays and H-alpha onset) and other one with the CME related shock. For RSP the delayed component definitely is related to a CME. Its spectrum extends with equal slope from relativistic up to moderate energies. But the impulselike RSP prompt component, in distinction from SEP of moderate energies, is not flare related. It rather connected to the hard X-rays [15] and type II radio emission which marks the early stage of a CME and the related shock.

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