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SPECTRUM OF ACCELERATED PARTICLES IN SOLAR PROTON EVENTS WITH A PROMPT COMPONENT

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Abstract

A new model of the source is suggested to describe solar proton events (SPEs) with two observed components of relativistic protons: the anisotropic prompt component (PC) and the isotropic global component (GC). The source of the prompt component lies high in the corona in the field reconnection zone of the magnetic bottle and the neighbouring magnetic arcade. The global component is assumed to originate at the magnetic bottle. The PC particles are accelerated by impulsive electric fields produced at current sheet disrupture in the reconnection zone. The PC emission spectra reconstructed for the events of 23.02.1956, 7.12.1982, and 16.02.1984 reveal a satisfactory agreement with the model calculations. The model also allows a consistent description of the source location, the intensity time profile, the spectrum and anisotropy of SCR in the extraordinary event of 16.02.1984.

Introduction High accuracy of the neutron supermonitors of SNM-64 type recording the ground-level enhancement (GLE) of solar cosmic rays (SCR) allows the evolution of a solar proton event in the range of particle rigidities $R \gtrsim 1$ GV to be traced to within 1 min, and some interesting features to be revealed in SCR distribution at the Earth orbit and near the Sun. For example, the data obtained recently for some particular events provide evidence [1-3] for a possible existence of two proton components - an anisotropic prompt component (PC) and an isotropic slow component (SC). According to our estimates, the GLE events of 23.02.1956, 4.05.1960, 20.07.1961, 18.11.1968, 7.05.1978, 7.12.1982, 16.02.1984, and probably of 19.11.1949 can be classified as events with a prompt component (class I), though in the latter case the data are insufficient. The events of this class are characterized by short duration, hard spectrum, and strong anisotropy, especially, before and near t_m maximum. The events of class II usually have a "diffusive" intensity time profile I(t) and are distinguished by their weak post-maximum anisotropy (a typical example is the GLE of 12.10.1981). In some cases (e.g. 23.02.1956 and 7.12.1982) both components could be isolated (Fig. 1), whereas in others, like 16.02.1984, only the prompt component was apparently recorded. All events of class I are associated with solar flares observed near the W limb. Of special interest is the GLE of 16.02.1984 for which no source (flare) in the visible disk was identified (emission in H-alpha and soft X-rays was absent) and the expected heliolongitude ranged from $\lesssim 95°$W to $\sim 130°$W according to different estimates.

We believe [2,3] that the source of the slow component may probably be the magnetic bottle when opening [4] , and the prompt component is apparently generated in the magnetic reconnection region under stimulating influence of the coronal shock wave or the expanding magnetic bottle. Below, we make an attempt to simulate the properties of the PC source (magnetic topology, plasma and magnetic field parameters, acceleration mechanism) on the basis of the observed SCR data (spectrum, anisotropy, emission time) and the calculated generation spectrum at magnetic reconnection in two magnetic arcades or bottles high in the corona [5,6] (Fig. 2).

Source model and SCR generation spectrum Let us assume that the flare proper develops at the coronal heights $h \approx 0.07-0.14\, r_\odot$ (where $r_\odot$ is the solar radius) following the scenario described in [4]. When expanding, the flare-generated magnetic bottle gets in touch with the neighbouring magnetic arcade at the height $h \approx 0.5-1.0\, r_\odot$ (Fig. 2). As inferred from the coronal transient data [7], the plasma density at the top of the magnetic bottle can be several times as large as in the ambient corona ($n \sim 10^6-10^7$ cm^{-3} for $h \approx 0.5-1.0\, r_\odot$) and the magnetic field B ranges from units to tens of G. In further calculations, the parameters n and B are taken in this range and the length of the current sheet, L, in Fig. 2 is set equal to $\sim 0.1\, r_\odot \simeq 10^{10}$ cm. As shown in [8-10], an additional flux of accelerated particles may appear in such configuration (Fig. 1) with a maximum preceding that of the flare-generated flux. The generation spectrum of the additional flux must have the form:

$$N_\odot(\mathcal{E}_k) = N_0 (\mathcal{E}_k/\mathcal{E}_*)^{-1/4} \exp\left[-1.12(\mathcal{E}_k/\mathcal{E}_*)^{3/4}\right] \qquad (1)$$

where the spectrum parameters $\mathcal{E}_*$ and N_0 are connected with the source parameters by the following relations

$$\mathcal{E}_* = 8.236\cdot 10^{-3}(B^3 Ln)^{2/3} \text{ MeV} \qquad (2)$$

$$N_0 = 1.47\cdot 10^7 (nL^2/B\,\mathcal{E}_*) \text{ proton/MeV} \qquad (3)$$

The PC generation spectra have been calculated from (1)-(3) for three GLE: 23.02.1956, 07.12.1982, and 16.02.1989. Besides, the behaviour of the prompt component at the Earth orbit has been analyzed to estimate its spectrum for the three above-mentioned events at the moment of emission [11]. The obtained spectra have been compared with each other and with the integral SCR flux emission spectrum. The results are shown in Figs. 3-5 for the events of 23.02.1956 ($B = 30$ G, $n = 2\cdot 10^7$ cm^{-3}, $L = 1010$cm) 7.12.1982 ($B = 20$ G, $n = 2\cdot 10^6$ cm^{-3}, $L = 0.2\cdot 10^{10}$ cm), and 16.02.1984 ($B = 20$ G, $n = 5\cdot 10^6$ cm^{-3}, $L = 0.2\cdot 10^{10}$ cm), respectively.

Discussion of results As seen from Figs. 3-5, the PC generation spectrum lies below that of the global flux and merges with that at R = 3-4 GV. This may infer that at high energies

SCR flux is determined by the prompt component alone. The calculated PC spectra are in a good agreement with the source spectra obtained from observations in the range of $\mathcal{E}_K = 0.3$ - - 5 GeV. This corroborates the suggested PC generation mechanism. At the same time, the calculated PC generation spectra in the low-energy band lie below the observed spectra. This discrepancy may be due to the neglected contribution of soft particles generated at the flare impulsive phase and escaping from the closed magnetic configuration (Fig. 2d). In the range of very high energies ($\mathcal{E}_K \geqslant 5$ GeV), the observed PC flux tends to exceed the calculated value, which may be due to contribution of the particles trapped in the magnetic bottle.

From the estimates given in [11] and from the results reported by other authors one can draw the following important conclusion concerning the source location and the mechanisms of SCR generation and emission in the event of 16.02.1984: the PC source was located in the vicinity of a favourable Sun-Earth connection heliolongitude $\theta_\delta \approx 82°$W and the acceleration and emission of particles occurred in the magnetic configuration illustrated in Fig. 2. This hypothesis consistently accounts for the time parameters and the hard spectrum of PC and a strong anisotropy of the observed SCR flux. It may also be applied to other GLE events.

<u>Conclusions</u> **Analysis** of the observed and the expected PC properties infers the following conclusions:

1. Generation of PC particles occurs at the heights of 0.5-1.0 $r_\odot$ in the reconnection zone of the magnetic bottle and the neighbouring magnetic arcade.

2. The suggested mechanism of acceleration in the current sheet electric fields accounts for the properties of the PC particle spectrum in the energy range of 0.3-5 GeV. Description of the integral SCR spectrum requires combined acceleration models.

3. The remoteness of the site of PC generation and emission from the flare may be due to the fact that the current sheet in which PC particles are accelerated develops at the periphery of the magnetic bottle (at a distance up to 50° in longitude from the site of the flare).

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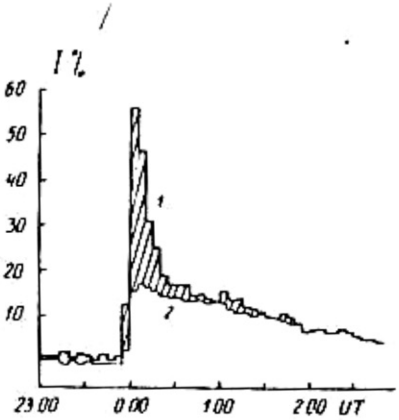


Fig.1.Kerguelen (1) and Deep River (2) NM-64 data of SPE 7-8.12.1982.

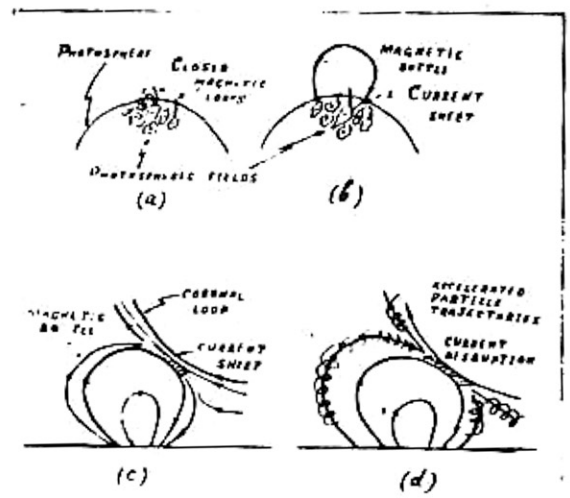
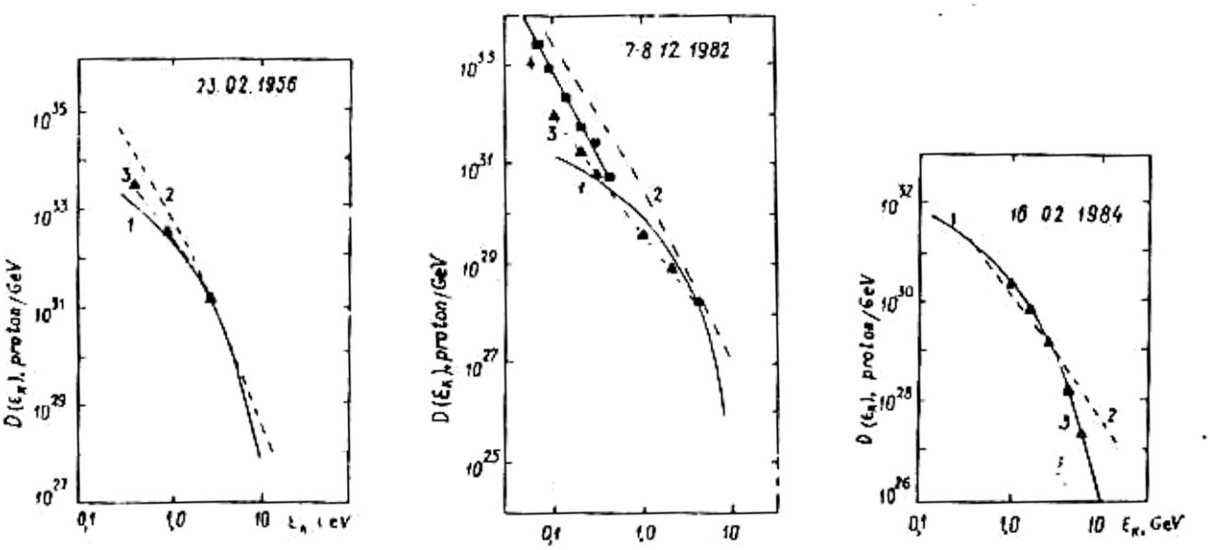


Fig.2.Source MG model.



Figs.3-5.SCR spectra for three SPEs: 1-calculated generation PC spectrum; 2-reconstructed emission spectrum for total SCR flux; 3-PC emission spectrum; 4-source SCR spectrum obtained by gamma-ray data.