Relativistic Solar proton Dynamics in Large GLE of 23rd Solar Cycle

Eduard V. Vashenyuk,[1] Yuri V. Balabin,[1] Boris B. Gvozdevsky[1] ....
(1) Polar geophysical Institute, Russian Academy of Sci., Apatity 184200, Russia

Abstract

The primary relativistic solar proton (RSP) parameters during the largest ground level enhancements (GLE) of 23 solar cycle: 14 July, 2000 and 15 April, 2001 have been obtained by modeling of the responses of neutron monitors of the worldwide network and comparing them with observations. The modeling comprised an optimization procedure as well as proton trajectory calculations in the up-to-date magnetosphere model Tsyganenko-2002 (T202). The spectra, pitch-angle distributions and anisotropy of RSP obtained for successive moments of time allowed to study the dynamical changes of these parameters during the events.

1. Introduction

Two GLEs: July 14, 2000 and April 15, 2001 are dominating in their amplitude over the 23 solar cycle. The increase was registered on the large number of neutron monitor stations in these events, that allowed to apply a modeling technique to definition of solar proton parameters on data of a ground based observations [1–3]. The analysis of dynamical changes of spectrum, pitch-angle distribution (PAD) and anisotropy of solar protons obtained in successive moments of time reveals the existence of two distinct populations of relativistic solar protons (RSP): rigid and anisotropic prompt component (PC) and the delayed component (DC) with a soft energetic spectrum and low anisotropy. The parameters of solar protons in the GLE of 15.04.2001 we describe here for the first time. What about the 14.07.2000 GLE studied earlier by us [3] and also in [4], we make some revision of former results with data correction of NM stations registered a superfluous increase because of direct penetration of RSP through the postnoon magnetopause (Apatity in the 14.07.2000 GLE and Oulu in the GLE 15.04.2001) [5]. Besides during preparing of this paper we calculated the cosmic ray arrival asymptotic directions with the up-to-date magnetospheric model T2002 [6], instead of the widely used earlier T1989.

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2. Modeling technique

The modeling technique of the neutron monitor response to an anisotropic solar proton flux [1–4] included definition of asymptotic viewing cones of neutron monitor stations under study by the particle trajectory computations in a model magnetosphere T2002 [6]. Determination of the anisotropic solar proton flux parameters outside magnetosphere was carried out by optimization methods based on comparison of computed neutron monitor responses with observations. We used the following form of response function of a neutron monitor to anisotropic flux of solar protons [1]:

$$\left(\frac{\mathrm{dN}}{\mathrm{N}}\right)_{\mathrm{j}} = \mathrm{K} \cdot \sum_{\mathrm{R}=1}^{\mathrm{R_{max}}} \mathrm{J(R)} \cdot \mathrm{S(R)} \cdot \mathrm{G_j(R)} \cdot \mathrm{F}\lceil{}^{\Theta}\mathrm{j(R)}\rceil \quad (1)$$

where dN/N is relative (to the GCR background) response of j-th neutron monitor, normalized to atmospheric pressure by the 2-attenuation length method [7], $\mathrm{J}_{\|}(\mathrm{R}) = \mathrm{J_O R}^{-\gamma}$ is rigidity spectrum of RSP flux in the direction of anisotropy axis. γ monotonically increases in rigidity and $\Delta\gamma$ is increase per 1 GV [2], S(R) is specific yield function [8], $\mathrm{F}(\theta(\mathrm{R}))\sim \exp(-\theta^2/\mathrm{C})$ is a pitch-angle distribution (PAD) of RSP in the IMF [1], $\theta(\mathrm{R})$ is angle between the direction of maximum intensity of particles and asymptotic direction of at given rigidity R. These parameters are determined with a least square procedure [9] by resolving a system of constrained equations.

3. Results of modeling

The event 14.07.2000 (≪Bastille Day GLE≫) was caused by a solar flare 3B/X5.7, originating at ∼ 10.20 UT near the center of solar disc (N22 W07). In our analisys we used data of 24 neutron monitors of the worldwide network. Fig. 1a shows the energetic spectra and Fig. 1b the pitch-angle distributions (PAD) of relativistic solar protons derived in successive moments of time. The spectrum (1) at the early stage of event is very hard and exponentially depends on energy [10]. The PAD for this time is the most narrow and widens then, being however rather nonstationary (Fig. 1b). This fact was also noted in [4]. The spectral form has radically changed already at 11.05 UT and did not vary then until 12.30 when intensity at high energies has essentially dropped. The modeled spectra agree rather well with data of direct solar proton measurements on balloons [11] and GOES-10 spacecraft also shown in Fig. 1a.

The event of 15.04.2001. The cause of the event was a solar flare 2B/X14.4, heliocoordinates S20W85 which started at 13.36 UT. In Fig. 2a, b the spectra and PAD of relativistic solar protons in their dynamics are shown in the same manner as in Fig 1. Likely the event of 14.07.2000 the very hard spectrum was observed right at early times when the PAD was the most narrow.

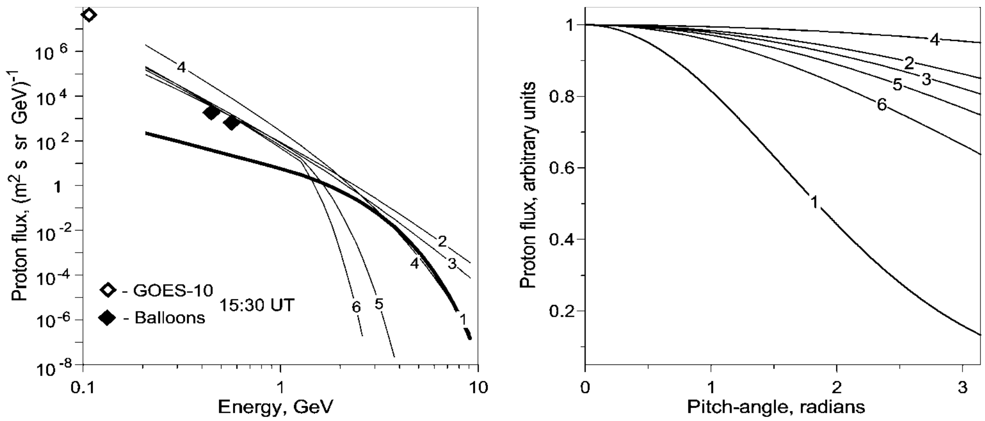

Fig. 1. **a**: derived energy spectra of RSP, **b**: pitch-angle distributions (PAD) at different moments of time on 14 July, 2000 that are: 1-10.40, 2-11.05, 3-11.30, 4-12.00, 5-12.30, 6-13.00. Thick line in Fig.1a is spectrum of prompt component of RSP. The balloons and GOES 10 points are data of direct solar proton measurements.

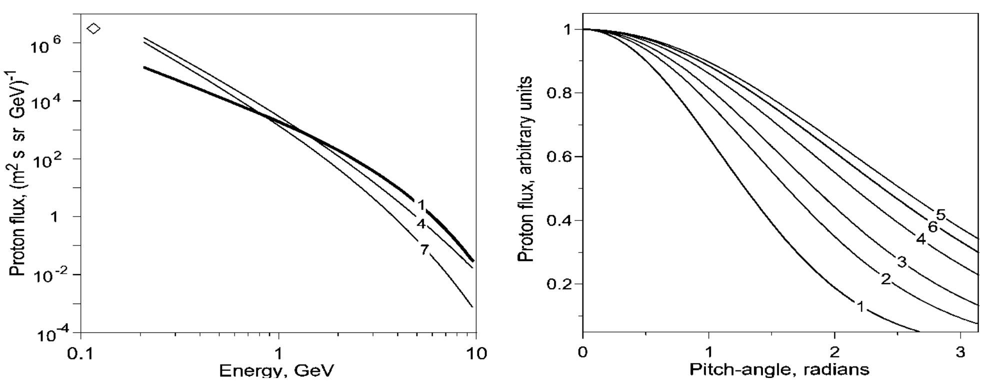

Fig. 2. The same as in Fig.1 The moments of time are: 1-14.10, 2- 14.20. 3- 14.30, 4-14.40, 5-15.00, 6-15.30, 7-16.00

The spectrum has steepened promptly in the next 20 minute and then did not changed markedly until 16 UT. The PAD monotonously widened up till the end of event.

Summary.

On data of modeling responses of the worldwide neutron monitors the dynamical behavior of the relativistic solar protons in the GLE 14.07.2000 and 15.04 2001 have been analyzed. The two populations of RSP: prompt, rigid and anisotropic and delayed one, with a soft energetic spectrum and low anisotropy, originated probably from different sources on the Sun were shown to exist in both

GLEs.

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