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RELATIVISTIC SOLAR PROTON DYNAMICS IN LARGE GLE OF 23rd SOLAR CYCLE

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Abstract. Basic parameters of relativistic solar protons (RSP) in the largest ground level enhancements (GLE) of the 23d solar cycle of 14 July, 2000 and 15 April, 2001 have been obtained by modeling the responses of the neutron monitors of the worldwide network and comparing them with observations. The modeling included an optimization procedure, as well as proton trajectory calculations, in the up-to-date magnetosphere model (Tsyganenko 2001). The spectra, pitch-angle distributions and anisotropy of RSP were obtained for several successive times allowing one to study dynamical changes of these parameters during the events. Two populations of RSP, the prompt and delayed ones, originated, probably, from different sources on the Sun were shown to exist in both GLEs. The prompt component (PC) of RSP has an impulsive intensity profile, hard, often exponential energetic spectrum and strong unidirectional anisotropy. The delayed softer RSP component seems to originate in a stochastic acceleration process. The delayed RSP component is sometimes associated with a bidirectional anisotropy, which may be an indication of a loop-like IMF structure associated with a CME.

Introduction

Two GLEs on July 14, 2000 and April 15, 2001 are dominant with respect to their amplitude over the 23^d solar cycle. The increase was registered at a large number of neutron monitor stations in these events, that allowed to apply modeling technique to define solar proton parameters using data of 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 an existence of two distinct populations of relativistic solar protons (RSP): rigid anisotropic prompt component (PC) and delayed component (DC) with a soft energetic spectrum and low anisotropy. The parameters of solar protons in the GLE of 15.04.2001 are described here for the first time. As for the 14.07.2000 GLE, studied earlier by us [4] and also in [5], 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 post noon magnetopause (Apatity in the GLE of 14.07.2000 and Oulu in the GLE of 15.04.2001) [6]. Besides, in the present study we calculated the cosmic ray arrival asymptotic directions with the up-to-date magnetospheric model T2002 [7], instead of the widely used earlier version T89 [8].

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 particle trajectory computations in a model magnetosphere T02 [7]. Determination of anisotropic solar proton flux parameters outside the magnetosphere was performed 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]:

$$\left(\frac{dN}{N}\right)_j = K \cdot \sum_{R=1}^{R_{max}} J(R) \cdot S(R) \cdot G_j(R) \cdot F\left[\Theta_j(R)\right] \qquad (1)$$

where dN/N is the response of the j-th neutron monitor, normalized to atmospheric pressure by the 2-attenuation length method [8,9], $J_{\|}(R) = J_O R^{-\gamma}$ is rigidity spectrum of RSP flux in the direction of anisotropy axis. γ monotonously increases in rigidity and $\Delta\gamma$ is the increase per 1 GV [2], S(R) is specifically set function [10], $F(\theta(R)) \sim \exp(-\theta^2/C)$ is the pitch-angle distribution (PAD) of RSP in the IMF [1], $\theta(R)$ is the angle between the direction of maximum intensity of particles and asymptotic direction at a given rigidity R. These parameters are determined with a least square technique [11] by solving an equation system.

Results of modeling

The event of 14.07.2000 («Bastille Day GLE») was caused by the solar flare 3B/X5.7, originated at ~ 10.20 UT near the center of the solar disc (N22 W07). In our analisys we used data of 24 neutron monitors of the worldwide network. Fig.1 shows the energetic spectra (a) and pitch-angle distributions (PAD) (b) of relativistic solar protons derived for successive moments of time. The spectrum (1) at the early stage of an event is very hard and depends exponentially on energy [12]. The PAD at this stage is the narrowest and then widens, being, however, rather nonstationary (Fig. 1b). This feature was also mentioned in [5]. The spectral form has radically changed already at

11.05 UT and did not vary then until 12.30 when intensity at high energies essentially dropped. The model spectra agree well with the data of direct solar proton measurements on balloons [13} and GOES-10 spacecraft (also shown in Fig.1a).

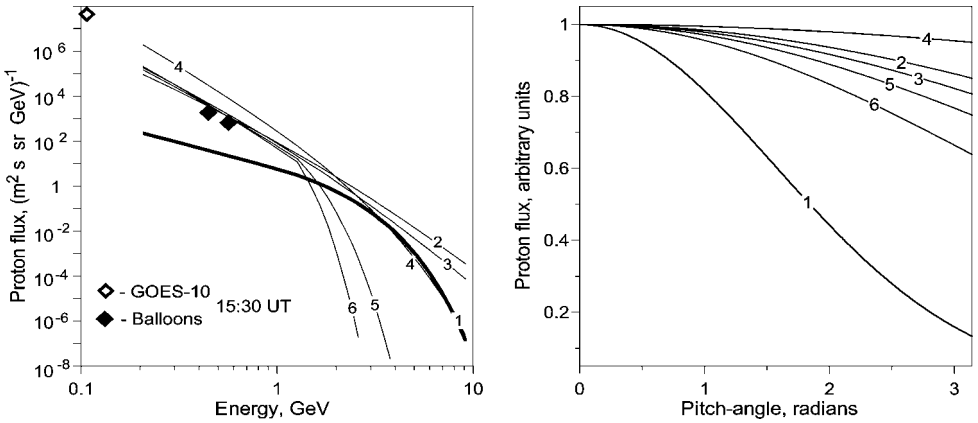

Fig1. (a) Derived energy spectra of RSP, (b) Pitch-angle distributions (PAD) at different times on 14 July, 2000; the time moments are: 1-10.40, 2-11.05, 3-11.30, 4-12.00, 5-12.30, 6-13.00. The thick line in Fig.1a is the spectrum of prompt component of RSP. The balloons and GOES-10 points are the data of direct solar proton measurements

The event of 15.04.2001. The cause of the event was the solar flare 2B/X14.4, heliocoordinates S20W85, which started at 13.36 UT. In Fig.2 a, b the spectra and PAD of relativistic solar protons in their dynamics are shown in the same manner as in Fig 1. As in the event of 14.07.2000, a very hard spectrum is observed right at the beginning of the event when the PAD is the narrowest. The spectrum has radically changed its form after 14.30 and then did not change for the next 2 hours The PAD monotonously widened up to the end of the event.

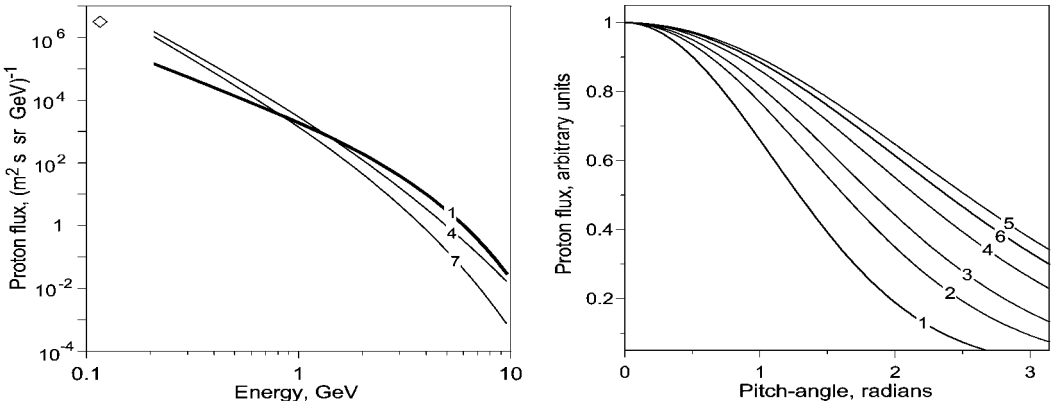

Fig. 2. The same, as in Fig.1, but for the event of 15.04.2001. The moments of time are: 1-14.10, 2- 14.20. 3- 11.30, 4-12.00, 5-15.00, 6-15.30, 7-16.00

Summary

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

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