High-Energy Cutoff for Solar Cosmic Rays by the Data of Large Non-Standard Detectors

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Abstract

A problem of the upper energy limit for solar cosmic rays (SCR) is studied. Formerly, this limit has been estimated mostly by the data of world network of standard detectors of cosmic rays — neutron monitors, muon telescopes and ionization chambers. Recently, it became possible to use for this purpose also the data of some large non-standard detectors (Baksan Underground Scintillation Telescope - BUST, Extensive Air Shower (EAS) Arrays like Carpet and Andyrchy, Project GRAND Array and others). Even though those detectors have been designed for resolving quite different nuclear and astrophysical problems, nevertheless, they proved to be sensible to the effects caused by powerful sporadic manifestations of the solar activity. These observations allow to advance into the energy range above 100 GeV and understand more distinctly the extreme potentialities of solar accelerators.

1. Introduction

Since a historical beginning of the SCR studies (February 1942) up to July 2002, in all 63 Ground Level Enhancements (GLE) of relativistic solar protons have been observed by the worldwide network of cosmic ray stations. The most of GLEs have been recorded by the standard neutron monitors (NM), muon telescopes (MT) and ionization chambers (IC), their effective energies at the sea level being at about 4–6 GeV, 15–20 GeV, and 25–35 GeV, respectively. Those observations allowed estimating a maximum energy (or rigidity) of SCR, E_m (or R_m), in fact, at the upper limit of geomagnetic cutoff rigidity R_c (around $R_c = 17$ GV at the geomagnetic equator). Indeed, in the case of giant GLE of 23 February 1956 (the largest one through 60 years of observations), by the standard detector data, an estimate was obtained $\mathrm{R_m} = 20.0\ (+10, -4)$ GV [1].

If one uses the data of non-standard arrays, a possibility arises to advance into the energy range above 20 GeV. For example, by Indian non-standard (inclined) MTs, on 23 February 1956 solar protons have been recorded in the range of 35–67.5 GeV [2]. The observations by underground detectors oriented towards the Sun seem to allow to advance into the energy range of $\sim$ 100–200 GeV [3].

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Table 1. Parameters of the upper limit spectrum (ULS) for SCR

Energy, E_p, eV	$>10^6$	$>10^7$	$>10^8$	$>10^9$	$>10^{10}$	$>10^{11}$
Exponent, γ	1.0	1.45	1.65	2.2	3.6	>4.0
$I(>E_p)$, $cm^{-2}s^{-1}sr^{-1}$	10^7	10^6	3.5×10^4	8×10^2	1.2×10^0	7×10^{-4}

For several decades, those observations do not find a satisfactory explanation in the framework of existing theoretical concepts of particle acceleration mechanisms at the Sun [4]. Moreover, since a large solar event of 29 September 1989 [5], the observational situation became considerably complicated: for the first time, the arrival of SCR to the Earth was fixed not by standard ground-based detectors only, but also by several underground MTs. A unique increase of 43% was seen in total counting rate at the Carpet detector at the Baksan Neutrino Observatory, BNO). The effect of this flare was also identified as a burst of muon intensity of 5σ at the BUST where the threshold energy of muon registration is $E_\mu \sim 200$ GeV that corresponds to the energy of primary protons $E_p \geq 500$ GeV [6, 7]. Afterwards, several other muon bursts at the BUST proved to be statistically significant (at the level of $\geq 3\sigma$ and related to certain GLEs ("Baksan effect") [4, 7].

In fact, these results gave a new incentive to the search for the upper limit energy of SCR by the data of non-standard detectors of cosmic rays [8–14]. In particular, by the data of EAS Array Akeno [8] some evidence was obtained that during the flare of 4 June 1991 solar neutrons at the energy ≥ 10 GeV were produced by relativistic protons with the energy $E_p \geq 10$ GeV. At the same time, measurements by large muon detectors at the GRAPES III Array (Ooty) in the period of March 1988 – January 1999 yielded no results of statistical significance [9]. On the other hand, observations at the Milagrito array during the flare of 6 November 1997 [10] allowed to find a certain effect in the high-energy channel. Although the registration thresholds for this detector are not known precisely, it is fair to state that the energy of arriving protons was wittingly above 10 GeV. Presumably, the maximum proton energies were considerably higher. Below available data are briefly discussed in the framework of the concept of upper limit spectrum (ULS) for SCR [15].

2. Results and Discussion

Table 1 presents main parameters of the ULS for the integral fluxes of solar protons in extended range of energies, at least, between $E_p \geq 1$ MeV and $E_p \geq 10$ GeV [15]. The ULS is shown by "a limiting curve" 15 in Figure 1 [4].

The data in Figure 1 form a fiducial interval of SCR fluxes to characterize maximum potentialities of the solar accelerators in high-energy range. There are

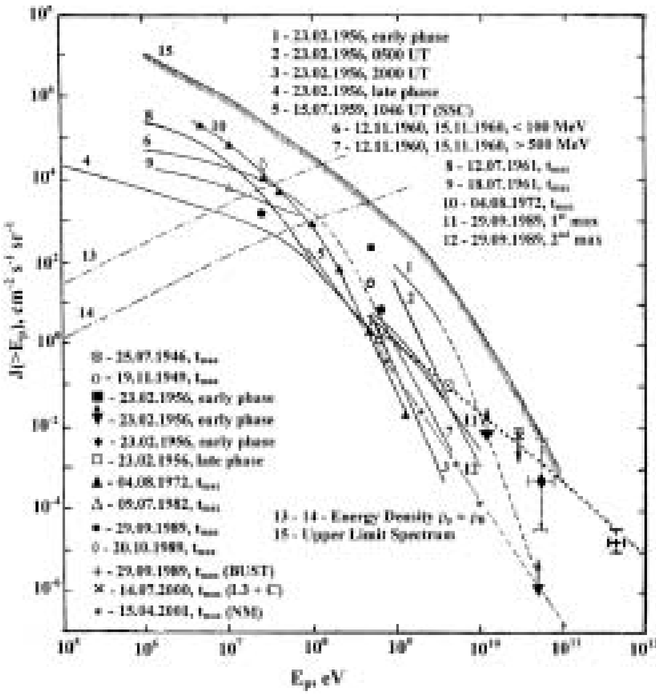

Fig. 1. Integral energy spectra near the Earth for the largest solar proton events of 1946–2002. The upper limit spectrum is represented by a rounding curve 15. The spectrum for galactic cosmic rays at $E_p \geq 500$ MeV is also shown (dotted line).

of interest the spectrum estimates [15] for the GLE of 23 February 1956 by the data of standard surface detectors (turned over triangles) and non-standard (inclined) muon telescopes (black diamond). For a comparison, we show an estimate of the upper intensity of solar protons at $E_p \geq 30$ GeV (cross) for the event of 14 July 2000 (BDE, or Bastille Day Event) by measurements of high-energy muon flux in CERN [11] (L3 Collaboration + Cosmic Muon Spectrometer). There is also presented an estimate of absolute flux of primary protons at $E_p \geq 500$ GeV estimated by the BUST data [6].

Certain hopes on the registration of solar flare effects has been set by the L3 Collaboration on the EAS detectors [12], however, a noted increase in their counting rates during the BDE requires an additional analysis. Supposedly, one can expect much more impressive effects from the flare of 15 April 2001, as it has been really observed, indeed [12–14].

Using the NM data we estimated maximum integral flux of relativistic solar protons observed near the Earth on 14 July 2000 and 15 April 2001, in standard units $cm^{-2}s^{-1}sr^{-1}$ (Table 2). Obviously, SCR spectrum for the BDE was very soft, and it could not cause statistically significant effects at non-standard detectors.

The GLE of 15 April 2001 was remarkable for harder spectrum, and it

Table 2. Integral fluxes of SCR on 14 July 2000 and 15 April 2001

R, ÃÂ	1	2	4	6	8	10
14.07.00	1.50×10^{0}	2.00×10^{-1}	9.50×10^{-4}	1.00×10^{-6}	2.50×10^{-9}	9.00×10^{-12}
15.04.01	2.00×10^{0}	3.70×10^{-1}	2.50×10^{-2}	2.90×10^{-3}	6.90×10^{-4}	1.60×10^{-4}

is also shown in Figure 1 for the rigidity range of 1–10 GV at the boundary of terrestrial atmosphere. The spectrum has a power-law form with a differential exponent about 4.0. Certain effects from solar protons have been recorded, in particular, at the detectors of Project GRAND Array (an increase of the muon intensity with a magnitude of 6.1σ) [13] and Andyrchy (about 10σ) [14].

According to the estimate [13], the increase of counting rate at the GRAND detector was due to solar protons, most probably with the energy around 100 GeV and the differential exponent of their spectrum about 2.0. To our opinion, such a value of the exponent at relativistic energies seems to be unrealistic, and the value of effective energy is evidently overestimated, too. When interpreting the data of the GRAND Array [13], the main difficulty comes from an absence of reliable response functions. The same difficulty is also characteristic for the Andyrchy Array [14] and other non-standard detectors.

3. Concluding Remarks

Even though the data in Figure 1 are still poor and fragmentary, they raise several questions of principal interest, *e.g.*: Are the particles really accelerated at the Sun up to the energy of $E_p \geq 500$ GeV, or some specific effect of modulation in the primary flux of galactic cosmic rays (GCR) takes place? The observations of the events like the GLEs of 29 September 1989, 6 November 1997 and 15 April 2001 by non-standard detectors clearly indicate solar relativistic protons well above 10 GeV (and probably ≥ 100 GeV). However, there is but few cosmic ray stations capable of measuring secondary muons from these protons, especially meaning that anisotropy information must come from single point measurements. This is difficult but feasible observational task for several MT stations with directional sensitivity [16].

A few new aspects of the problem under consideration arise due to production of medium energy neutrinos (> 1 GeV) by relativistic solar protons *in situ* (in the Sun's atmosphere) and possible detection of the flare neutrinos [17].

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4. References

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