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A study of the ground level enhancement of 23 February 1956

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Abstract

One of the greatest and most famous increase of solar cosmic rays over the neutron monitor epoch is the ground level enhancement in 1956. All future proton events are inevitable when compared with this one and therefore it is necessary to provide the efficiency of such a comparison derived from the existing data. In this paper, we return to the analysis of ground level observations on 23 February 1956 in order to model more precisely the solar cosmic ray behaviour. The extremely high magnitude of this effect allowed various spectral characteristics of solar cosmic rays, their anisotropy, differential and integral proton fluxes, and angular distribution of the source of solar particle anisotropy to be obtained with sufficient accuracy on the basis of available data from 13 neutron monitors. The most outstanding feature of this event was a narrow and extremely intensive beam of ultra relativistic particles arriving at Earth at the beginning of the event. This unique beam was not long and its width did not exceed 30–40°, thus, its contribution to solar particle density was not significant. Many features of this GLE are apparently explained by the peculiarity of particle interplanetary propagation from a remote (limb or behind of limb) source.

Keywords: Cosmic rays; Neutron monitors; Proton events; Ground level enhancements

1. Introduction

A ground level enhancement (GLE) is defined as a sharp increase of small duration in the counting rate of ground-based cosmic ray (CR) detectors caused by the accelerated charged particles from the Sun to the energies sufficiently high to be recorded at Earth.

Proton event on 23 February 1956 is the greatest ground level enhancement (GLE05) of solar cosmic rays ever recorded by neutron monitors. Since that time hundreds of proton events and tens of GLEs were registered, but all of them rank below this one by more than one order of magnitude. The superiority of this event over all others is demonstrated in Fig. 1, where the biggest variations of neutron monitor (NM) counting rates during the proton events in 19 (February 23, 1956), 22 (September 29, 1989), and 23 (April 15, 2001) cycles are presented, as if they started at the same time. Unfortunately, during the year 1956 there were not so many types of observations as there are nowadays (Miroshnichenko, 2001). There were no solar wind measurements and we can only guess about IMF properties. Also there was no information on CMEs and very limited information about flares, without X-ray and gamma observations. The cosmic ray data were obtained by ground level detectors of small surface, and not always of standard design. However, the large magnitude of the enhancement is an advantage that dominates over all possible difficulties. Under such a great effect the statistical accuracy of detectors can be ignored.

In this work, cosmic ray intensity data from 13 neutron monitors for this extreme event has been

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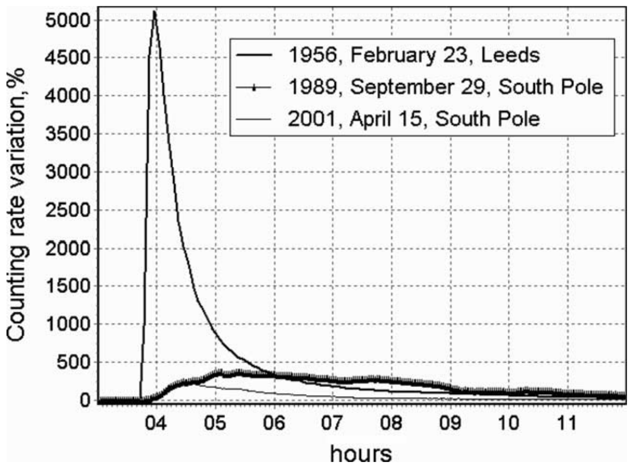

Fig. 1. Counting rate variations for the biggest GLEs recorded in different solar cycles. Time is shown for the GLE05. Other events are plotted as if their onsets occurred at the same hour.

analyzed and processed in order to model more precisely the behavior of solar cosmic rays. A complete analysis, including also data processing from other ground level detectors as well, will be presented soon elsewhere.

2. Background of the GLE05 event

The year 1956 falls into the increasing phase of solar cycle 19. A deep minimum of the solar activity took place in the year 1954. Spot generation became essentially faster at the end of 1955 and their monthly mean maximum reached the value 254 in October 1957. GLE05 was the first ground level proton enhancement in cycle 19. Flare activity increased at the end of October 1955 and grew more in January 1956. The majority of the flares were associated with the February spot group number 17351. During the time this spot group was moving from the visible part of the solar disk to the area behind the limb, a flare of 3B importance with coordinates N25W85, started on 23 February at 03:34 UT. The flare's position was close to the limb but we can not be driven into the conclusion that part of the spot surface was not located behind of limb as well; in this case the flare may have started earlier. After high maximum in 1954 the galactic cosmic ray (GCR) intensity almost did not decrease in 1955. The fall of intensity started just in February 1956, and for 10 GV particles reached 2.3% (Belov et al., 1997). Several consequent Forbush decreases lowered in total the GCR intensity by 11% (Climax) by the time of 20 February. A recovery started on 20–21 February and reached approximately 2.5% by 23 February. The shocks that arrived on 21 and 22 February apparently did not result in more decreases neither did they slow down the recovering. However, the CR intensity was lower in the base period than during the solar activity minimum (perhaps by 8–9% for 10 GV).

Geomagnetic activity was relatively low during the period 1953–1955. Only one magnetic storm (on 11–12 February) was recorded until the 25th of February. Large modulation effects in CR and sudden commencements (SSC or SI) during 11–22 February indicate a significance of the interplanetary disturbances. After the flare on 23 February, a magnetic storm started with a shock arrival on 25 February at 03:06 UT and reached the level of severe storm with $K_p = 8+$, the biggest one since April 1952. The geomagnetic activity in February 1956 and also these extreme cosmic ray events are presented in Fig. 2.

3. Cosmic ray variation model

The GLE05 in February 1956 was recorded by 13 neutron monitors that turned out to be very well distributed on Earth covering a rigidity range from 1 GV (Ottawa) to 11.35 GV (Norikura). Characteristics of all the stations used in this analysis are presented in Table 1.

Cosmic ray variations recorded by a ground level detector during a GLE may be written as follows (Dorman, 1963; Belov et al., 1994)

$$\frac{\Delta N}{N_0}(t,t_0) = \frac{\int_{E_c}^{E_u} W(E,t_0,h)\frac{\Delta I}{I_0}(t,E)\,\mathrm{d}E}{\int_{E_c}^{E_u} W(E,t_0,h)\,\mathrm{d}E}, \quad (1)$$

where I_0 is the galactic cosmic ray flux causing N_0 counting rate at the detector, h is the atmospheric depth of the point of observation in mb and E_u is the lowest value of the upper energy limit (Duggal, 1979), which in case of GLE05 is considered as 20 GV. Function $W(E, t_0, h)\mathrm{d}E = W(R, t_0, h)\mathrm{d}R\,\partial E/\partial R$ is the coupling coefficient taken as (Clem and references, 2000)

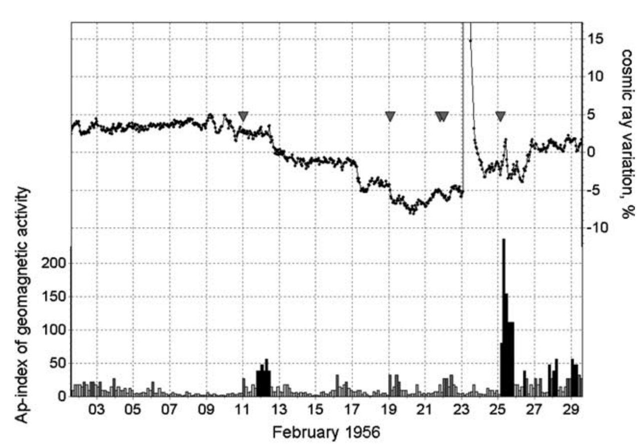

Fig. 2. Counting rate variations at Climax neutron monitor and Ap index of geomagnetic activity on February 1956. Great fluxes on 23 February are not plotted. Triangles in the top of figure correspond to the SSC times.

Table 1
Stations which data are utilized in this analysis

Station	Abbreviation	Lat	Long	Alt (m)	Ho (mb)	Rc(GV)
Albuquerque	albq	35.08	−106.62	1567	800.00	4.47
Arneb USS	arnb	−41.28	174.77	0	1013.00	3.45
Berkley	berk	37.87	−122.30	0	1005.00	4.55
Chicago	chgo	41.83	−87.67	49	1000.00	1.71
Climax	clmx	39.37	−106.18	3400	667.00	3.06
Gottingen	gott	51.52	9.93	273	1013.00	3.00
Leeds	leed	53.80	−1.55	100	1004.00	2.15
Mexico City	mxco	19.33	−99.18	2274	779.00	9.74
Mt. Norikura	mtnr	36.11	137.55	2770	888.00	11.35
Ottawa	otwa	45.44	−75.68	57	1008.00	1.08
Sacramento Peak	sacp	32.72	−105.75	3000	680.00	5.10
Stockholm	sthm	59.35	17.95	0	1000.00	1.50
Weissenau	weis	47.80	9.50	427	960.00	4.08

$$W(E,t_0,h)\,\mathrm{d}E=\begin{cases} W_{\min}(R,h)\cdot(1+\delta_{t0}(R))\cdot\frac{\partial E}{\partial R}\,\mathrm{d}R & E>2\,\mathrm{GeV},\\ W(2\,\mathrm{GeV},t_0,h)\cdot\left(\frac{E}{2\,\mathrm{GeV}}\right)^{3.17} & E<2\,\mathrm{GeV},\end{cases} \tag{2}$$

where $W_{\min}(R,h)$ are the coupling coefficients in the solar activity minimum, given by:

$$W_{\min}(R,h)=\alpha\beta\mathrm{e}^{-\alpha R^{-\gamma}}R^{-(\beta+1)}, \tag{3}$$

where $\alpha = \exp(1.84 + 0.094*h–0.09*\exp(-11*h))$; $\beta = 1.40 - 0.56*h + 0.24*\exp(-8.8*h)$ and $\delta_{t_0}(R)=a_0\frac{b_w+(10)^{\gamma_0}}{b_w+R^{\gamma_0}}$ is a typical spectrum for Forbush effects, where $a_0 = 0.08$, $b_w = 5$ GV, $\gamma_0 = 0.8$ and R is measured in GV. For energies $E <$ 2 GeV another coupling function (Belov and Struminsky, 1997) has been used

$$W(E,t_0,h)=W(2\ \mathrm{GeV},t_0,h)(E/2\ \mathrm{GeV})^{3.17}. \tag{4}$$

Cosmic ray intensity variations $\Delta I(t, E)$ in common were supposed to consist of two parts – isotropic part ΔI_0 and anisotropic one ΔI_1

$$\Delta I(t,E)=\Delta I_{0+}\Delta I_1=b_0f_0(E)+b_1f_1(E)\Psi_1(\chi,E), \tag{5}$$

where χ is the angular parameter of the solar CR anisotropy, Ψ_1 is the axis-symmetric function equal to 1 for $\chi\leqslant\chi_0$.

In our analysis several models have been sampled by their best fitting to neutron monitor data to describe spectrum and anisotropy of the solar CR during this event. Finally, a completely anisotropic model for the period 3:40–3:50 UT, an isotropic one – starting from 4:55 UT, and a mixed one – for the period 3:50–4:55 UT were applied. For ΔI we used power law spectra, whereas the angular distribution function was taken as $\Psi_1 = \exp(-n_a\sin(\chi-\chi_0)^2)$. The model for NM counting rate may be written as:

$$\left.\frac{\Delta N}{N_0}\right|_i(t)=b_0(t)C_{0i}(E_i,h,\gamma,E_\mathrm{u},t)+b_1(t)C_{1i}(E_i,h,\gamma,E_\mathrm{u},\lambda,\varphi), \tag{6}$$

where

$$C_{0i}=\int_{E_i}^{E_\mathrm{u}}W(E,t_0,h)R^\gamma(t,E)\,\mathrm{d}E\Big/\int_{E_i}^{\infty}W(E,t_0,h)\,\mathrm{d}E, \tag{7}$$

$$C_{1i}=\int_{E_i}^{E_\mathrm{u}}W(E,t_0,h)R^\gamma(t,E)\times\exp\left(-n_a^2\sin^2(\chi(E)-\chi_0)\right)\mathrm{d}E\Big/\int_{E_i}^{\infty}W(E,t_0,h)\,\mathrm{d}E \tag{8}$$

and parameters b_0, b_1, γ, E_u, n_a and χ_0 are time-dependent. Instead of χ_0 two other parameters are defined, the latitude λ_0 and the longitude φ_0 of the anisotropy source, so that the total maximal number of searching parameters becomes seven. Their behavior was calculated by the least square method. Unfortunately, we can not find reliably the up energy limit E_u from neutron monitor data in this case. The maximal cut off rigidity, at which the enhancement was still observed at fixed moment (~40 GeV), gives low limit of Eu, but in the higher energy region the residual dispersion changes hardly. Thus, E_u is the least considerable parameter among the all calculated, and it might be even put in without big damage. This indefinite may be cleared up after analysis of the data from muon telescopes and ionization chambers.

4. Results and discussion

One can see from Fig. 3 that the mean flux of CRs, considered as their density, increases fast just after the onset and for energy 1 GeV reaches the maximum $4\times10^{-4}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ in about 55 min. At the beginning of the event the spectrum of solar CR turned out to be hard. The spectral index fall down up to $\gamma = -3.1 \pm 0.5$ at 3:50–3:55 UT. During the next 45 min the absolute value of this index increased fast and during the rest time exceeded the value of 5. Analogous

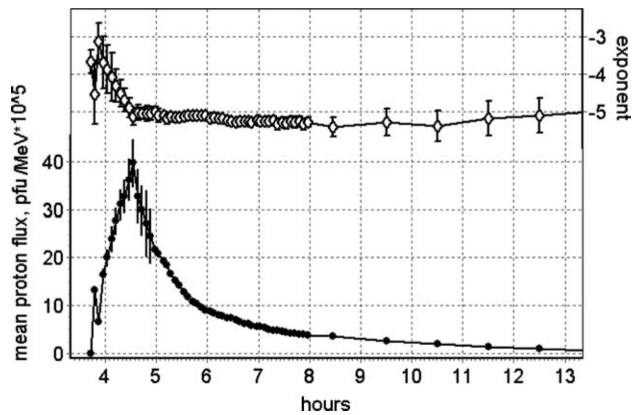

Fig. 3. Behavior of the power law index for isotropic (starting from 6th 5-min interval), and anisotropic (the first 15 5-min intervals) models together with the mean proton flux, averaged over all directions of 1 GeV energy.

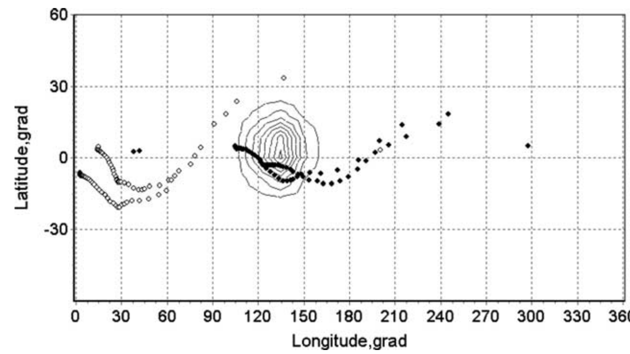

Fig. 5. Location of the solar CR anisotropy source at 3:40–3:50 UT (isometric curves of the equal fluxes) and asymptotic directions of vertical incident particles with energy <15 GeV for two stations (Gottingen and Leeds) with maximal effect (black points) and two stations (Ottawa and Chicago) with zero effect at this time (opened circles).

behavior of spectral index is sufficiently typical for GLEs. For example similar variations were observed in September 1989 (Baisultanova et al., 1990, 1992). After 11:00 UT a tendency to harder spectrum appears, but this result seems to be less reliable. In this time the effect from solar CR became small and comparable with the possible false variations in the NM counting rate.

A fast decline of the high-energy particle flux is evident in the integral representation of protons in Fig. 4. Of course, presented results for energy >300 MeV and moreover, >100 MeV are obtained by extrapolation. No NM registers CR with energy <500 MeV, and corresponding profiles of low energy CR are obtained in assumption that the shape of the spectra and the γ-index do not depend significantly on the energy. Nevertheless, it is interesting to compare obtained estimations with later real measurements onboard IMP-8 and GOES satellite series. The biggest proton fluxes (about 600 pfu) for energies >100 MeV were recorded on 29 September 1989 and 14 July 2000. Thus, the estimated flux for >100 MeV particles in February 1956 exceeds only twice the values observed during satellite epoch.

At the beginning of the event the particles arrived by a very narrow beam. The location of the particles, calculated by the method mentioned above, as well as the asymptotic directions of the stations with the biggest effect (black points) and of those without effect (opened circles) is shown in Fig. 5. For the angular dependence $n_a = 8$, the outward curve corresponds to a flux of 0.1 from maximum. The asymptotic directions are presented for vertical incident particles with energy <15 GeV for two stations with maximum and two others with minimum (in fact, zero) effect. One can see that these directions are closed to each other. If the angular distribution was even 1.5 times wider, this effect would be observed by all stations. Our results are in agreement with Smart and Shea (1990), complementing and extending them.

The most outstanding feature of the proton enhancement on 23 February 1956 is that a narrow and extremely intensive beam of ultra relativistic particles arrived at Earth at the beginning of the event. Several neutron monitors fell under this beam and recorded extremely big cosmic ray enhancements. Up to now none of the sixty two GLEs that followed the one in 1956 revealed values comparable in magnitude with those of this effect. However, this unique beam was not long and its width did not exceed 30–40°. So, its contribution in solar particle density or in their fluence was not very important. Estimation of integral flux of >100 MeV particles put this event above all next ones, but it does not outstand herewith from the common distributions. The data-extrapolation for 10 MeV particles seems to lead to the idea that although this event is one of the largest, however it is not unique. Similar narrow beams at the beginning of a GLE have been observed also in other events (for example, in GLE65 and 66 in October 2003). These phenomena appear to be described by

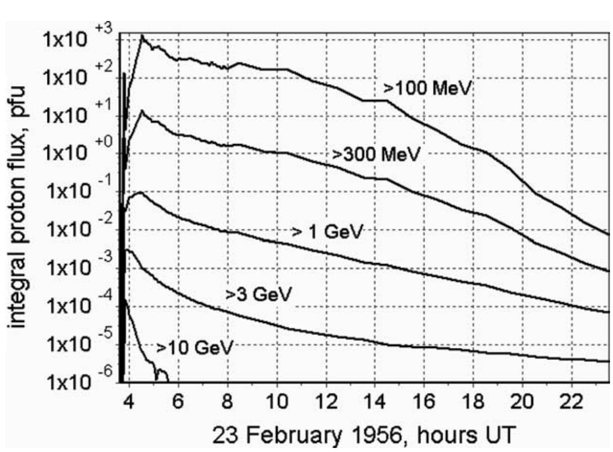

Fig. 4. Integral flux of protons with the energies >100 MeV, >300 MeV, >1, >3 and >10 GeV.

means of a non-diffusive particle pulse transport with a kinetic theory approach (Fedorov et al., 2002).

Although the available dataset used in this analysis gave a lot of information for the considered event, some uncertainties continue to exist due to the quality of these data. These uncertainties regard to unusual changes of anisotropy characteristics and energy spectrum in the first 15 min, to the spectra changes during the end of the event and to hardening spectra along the energy increase as well. A joint analysis of data from NMs, ionization chambers and muon telescopes, operating at that time, is hopeful to give more definite answer considering the change of these specific parameters.

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