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A Model for the Enhancement of Very High Energy Particles During Large Solar Flares

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In recent years, some short-term enhancements of cosmic ray particles during large solar flares (GLE) were recorded by neutron monitors at sea level and underground muon detectors at different depths. The energy regions concerned have reached to several hundred GeV, even to a few TeV. It is discussed in this paper that the flux enhancement in the TeV region may be the result of re-accelerations of the galactic cosmic rays during large solar flares. Because of the steepness of the energy spectrum of cosmic rays, the re-acceleration of a small part of cosmic ray particles in the GeV region may induce the obvious enhancements of cosmic ray flux in the TeV region.

Key words: solar flare, cosmic ray, flux enhancement.

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1. INTRODUCTION

A series of large solar proton events, which follow solar flares, occurred from August to October 1989. These events have been recorded by a Japanese meteorological satellite in the energy region of 4-68 MeV for protons and 8-370 MeV for alpha particles. In the 21^{st} solar period, the event with highest particle flux was observed on 20 Oct., but the biggest ground level event (GLE) occurred on 29 Sept. This event has been recorded by all of the neutron monitors in the world. The energy spectrum of this event can be obtained from satellite and neutron monitor data and seems to be a simple power spectrum with the power index of $\gamma = -2.6$ in the energy region of a few MeV to 10 GeV [1].

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This event is also recorded by the combined ground-based and underground array for high-energy cosmic rays operated in Yakutsk, Russia [2]. This array consists of a neutron monitor 18NM64, a large ionization chamber ASK-1, and 3 muon telescopes MT-6 situated at three different underground levels. After careful analysis, they concluded that there were particles with energy of 2-150 GeV produced in this event. The correlation between the short-term enhancement of muons and the solar flares has been studied by the Baksan collaboration using an underground scintillator telescope [3]. Among the five events with obvious positive correlation, the GLE event on 29 Sept. 1989 has the largest statistical significance, $\sigma = 5.5$. The energy threshold of the Baksan detector is larger than 200 GeV. In this event, the short-term enhancement of underground muons has about a 1.5 hr time delay compared to that recorded by the ground carpet detector array. The particle energy spectrum has been estimated in Ref. [4] which shows that particles with energy $E \leq 10^{12}$eV were produced during the solar flare. A group of very high energy nuclear interaction events recorded in Aug. 1972 have been analyzed [5]. There are two 3B-large solar flares on 4-7 Aug., and the counting rates per day are higher than the average value with 3.6 σ and 3.3 σ. The corresponding energy region is about 10 TeV.

From the above observations, we can deduce that there are enhancements of high energy particles during a large solar flare with about 1.5 hr time delay. The main detectors used in these observations are large-area scintillation muon telescopes situated at different underground depths. Recently, some EAS arrays situated at high mountain levels have been put into operation with thresholds of about a few TeV. They are the potentially important tools to study this phenomena.

2. A MODEL FOR THE ENHANCEMENT OF THE FLUX OF VERY HIGH ENERGY COSMIC RAYS

It was observed by many experiments that enhancement of the flux of cosmic rays can reach to the energy region of several hundred GeV, even probably to 10 TeV. But no existing model can explain this phenomena. Authors of Ref. [5] gave an explanation to this phenomena. They proposed that some part of galactic cosmic ray particles can be re-accelerated to this energy region by the interplanetary shock wave that forms during large solar flares (especially several consecutive large solar flares, such as those from 2-7 Aug. 1972).

It is known that the differential energy spectrum of cosmic rays is as follows:

$$\frac{dN}{dE} = AE^{-\gamma}, \tag{1}$$

where A is a constant, and γ is the power index. The spectrum is very steep with an index of $\gamma \simeq 2.7$ when $E_0 \gtrsim 10^{11}$eV. During the period of solar flares, a part (η) of cosmic rays are re-accelerated and the average energy increment is ΔE, which is independent of the primary energy of the particle. From Eq.(1), we can get the increment rate of cosmic ray flux between energy E_1 and E_2:

$$R = \eta\left[\left(1 + \frac{\Delta E}{\bar{E}}\right)^{\gamma} - 1\right] \tag{2}$$

where

$$\bar{E} = \frac{\gamma - 1}{\gamma - 2} E_1 \left[1 - \left(\frac{E_1}{E_2}\right)^{\gamma-2}\right] \Big/ \left[1 - \left(\frac{E_1}{E_2}\right)^{\gamma-1}\right].$$

According to this model, the increment rate of cosmic ray particles in the 10 TeV region has been calculated by Monte Carlo simulations using Eq.(2). We assume that only 10% of cosmic ray particles

Table 1
The increment rate of cosmic ray flux in different energy regions.

E_p (TeV)	ΔE (GeV)	100	200	500
2.5 - 5	R (2)	0.82%	1.68%	4.53%
	R (MC)	1.03%	2.21%	7.01%
5 - 10	R (2)	0.41%	0.82%	2.13%
	R (MC)	0.48%	0.99%	2.72%
10 - 20	R (2)	0.20%	0.41%	1.03%
	R (MC)	0.22%	0.44%	1.12%
20 - 40	R (2)	0.10%	0.20%	0.51%
	R (MC)	0.14%	0.25%	0.59%

Table 2
The increase of counts at different energy regions for the YBJ array.

Increase of counts		ΔE (GeV)		
		100	200	500
E_p (TeV)	2.5 - 5	162 ± 125	347 ± 125	1103 ± 125
	5 - 10	521 ± 327	1062 ± 327	2902 ± 327
	10 - 20	212 ± 313	429 ± 313	1104 ± 313
	20 - 40	72 ± 228	131 ± 228	309 ± 228

have been re-accelerated during the solar flare, the increment rates of cosmic ray flux in different energy regions for different energy increase ΔE (100, 200, and 500 GeV) are shown in Table 1, where R (2) is obtained from Eq.(2), and R (MC) are the results of Monte Carlo calculations. It shows that the enhancement of cosmic ray flux in 10 TeV is detectable if we have enough observational data.

The Yangbajing EAS array (China-Japan collaboration, 4300 m above sea level, Tibet, China) is the ideal and efficient installation to observe this phenomena. The detection efficiencies for primary protons with energy 5, 10, and 50 TeV of the YBJ array at its first running period are about 3%, 31%, and 80%, respectively. The counting rate of the YBJ array is about 20 Hz. For a GLE event with a duration of 4 hours, there would be about 3×10^5 showers recorded by the YBJ array. Figure 1 shows the energy distribution observed by the YBJ array and the Monte Carlo calculations for those showers. According to our model, if we assume 10% of cosmic ray particles are re-accelerated during the large solar flare, and the energy increments are ΔE = 100, 200, and 500 GeV, respectively, the corresponding enhancements of showers recorded by the YBJ array are shown in Table 2. It shows that an enhancement with a significance of more than 5σ will be recorded by the YBJ array for η = 0.1 and ΔE = 200 GeV. Recently, the YBJ array has been extended, the counting rate is increased from 20 Hz to 200 Hz, and it will be more efficient to observe this phenomena.

3. DISCUSSION

In the four most recent solar active periods, many GLE events accompanying solar flares have been recorded, their energies reached to several tens of GeV, some even to a few hundred GeV [2-4]. It formed an energy spectrum covering a wide range of energy from these observational data. The

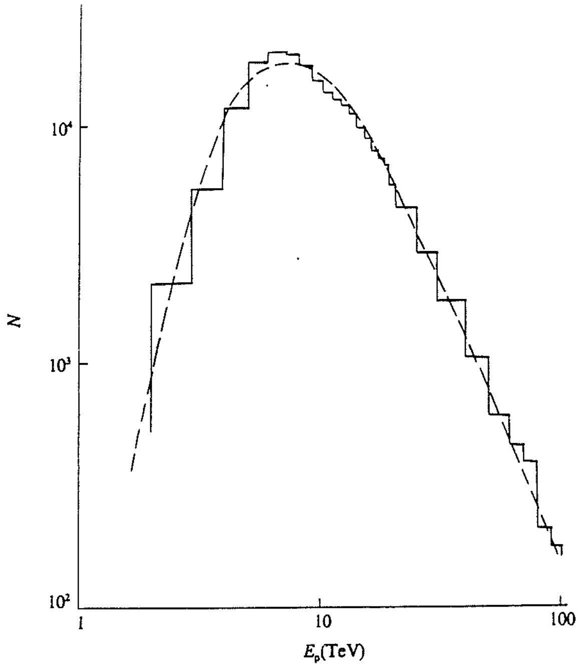

Fig. 1
The distribution of the counts of the Yangbajing experiment in 4 hours (solid circles) and the corresponding result from a Monte Carlo method (solid histogram).

different spectrum indices and the time characteristics of flux enhancement are very important to understand the acceleration mechanism of cosmic ray particles during solar flares, and further to deduce the production and acceleration process of cosmic ray particles in the interplanetary space. The observation result in Ref. [5] cannot be explained by the existing physical processes during solar flares and available acceleration models of solar cosmic ray particles. But the observational result in Ref. [5] can be explained by assuming that some part of galactic cosmic ray particles over 10 TeV are re-accelerated by the shock waves during large consecutive solar flares. There is no GLE event observed by ground level EAS arrays because of their high energy threshold (> 100 TeV) and low counting rates. On the other hand, it is possible for the EAS arrays situated at high mountain levels to observe GLE events because of their low threshold (several TeV) if the energy region of the enhancement is only a few TeV.

Our Monte Carlo result has proved this point of view and also explained the observational result in Ref. [5]. It is reported that the 23rd solar active period will be started this year (1995), and the most active time will be the years of 1999-2000. The best time to observe GLE events is nearing the maximum and it is also the best running time of the YBJ array after extension. These phenomena will be more clear after further accumulation and analysis of observation results.

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