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Spectra and solar energetic protons over 20 GeV in Bastille Day event

Ruiguang Wang [a,b,*], Jinxiu Wang [a]

[a] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[b] Institute of Science and Technology for Opto-Electron Information, Yantai University, Yantai 264005, China

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Abstract

Solar energetic particles (SEPs) from large solar flares give important information about the physical process in the solar corona and the heliosphere. Several observations have indicated that solar protons could sometimes be accelerated to at least tens of GeV, even hundreds of GeV, in intense solar energetic process. We studied the solar proton differential energy spectra with energy range of 1–500 MeV at several time intervals during Bastille Day event. It was shown that the spectra could be fitted by a power law function before flare and after flare the power law spectra still existed above 30 MeV although spectra became softer with time. There was a spectral "knee" occurring at ~30 MeV. We constructed a solar proton differential spectrum from 30 MeV to 3 GeV at peak flux time 10:30 UT and fitted it in the same manner. On the basis of a supposition of having the same power law spectrum in higher energy, we calculated the solar proton integrated fluxes in energy range of from 500 MeV to 20 GeV and compared them with other results obtained from experimental, modelling and theoretical calculations in other big historic SEP events. A Monte Carlo simulation was carried out for a primary proton beam at the top of the atmosphere producing secondary muons on the ground. Based on the simulation, possibility of registering the solar energetic proton beams with energies over 20 GeV was discussed.

Keywords: Solar flare; Solar energetic proton; Ground level enhancement; Solar energy spectra; Monte Carlo simulation

1. Introduction

It is known that solar energetic particles (SEPs) are accelerated during intense solar high energy process that are accompanied by coronal mass ejections (CMEs). The events in which particles with energy more than ~450 MeV may produce a solar cosmic ray flux enhancement near Earth and be registered by ground based detectors are referred to as ground level enhancement (GLE) events. Increased fluxes of SEPs in big GLE events allow us to obtain information about flare process and the particle acceleration mechanism. Generally, solar proton fluxes are registered by satellite-borne detectors in the energy range of 1–500 MeV, the worldwide neutron monitors (NMs) from 500 MeV to 15 GeV, and the ground or underground muon detectors in higher energy region. The NMs are the main instruments detecting secondary neutrons at ground level and showing the energy threshold of incident protons with the local geomagnetic rigidities. In the very big GLE of 29 September 1989, the Hunacayo NM with a rigidity cut-off of 13 GV, observed a significant (>10%) increase, suggesting that solar protons with energies higher than 12 GeV were present.

Compared to NMs, some directional detectors (such as muon telescopes) operating at higher energies should be better suited for detecting higher energy solar proton beams in big solar flares. Since energy thresholds are typically fixed by the instrument design and their atmospheric or underground depth, these instruments can register events, in principle, with energies up to or beyond 100 GeV. Using an underground muon detector with an equivalent rigidity of 19 GV, Embudo group observed a positive signal increase which was coincident in time with

* Corresponding author. Chinese Academy of Sciences, Institute of High Energy Physics, Center of Particle Astrophysics, 19B Yuquan Road, Beijing 100049, China.
E-mail address: wangrg@mail.ihep.ac.cn (R. Wang).

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the increases seen by NMs in the GLE of 29 September 1989. It was concluded that the upper rigidity of solar particles during this event would be approximately 25 GV [1]. Some other results mainly obtained from underground muon detectors have shown possible signals of higher energy solar protons [2–5]. Among them, the Baksan Group claimed that an observed excess of the muon flux in the same GLE should be induced by solar protons with energies higher than 500 GeV [6]. In the current solar cycle, the L3 Collaboration observed a small muon flux excess from a narrow sky cell by a high directional resolution muon spectrometer in the GLE of 14 July 2000 [7,8]. This excess was time-coincident with the peak increase seen by NMs, corresponding to primary proton energies above 40 GeV.

However, the information on solar relativistic protons in Bastille Day event is rarely available. In this paper we present solar energy spectra covering the energy range from 1 MeV to 3 GeV. The spectra were fitted by a simple power law in rigidity. Based on fluxes extrapolated to a little higher energy and a Monte Carlo simulation from a primary proton beam at the top of the atmosphere to secondary muons on the ground, we discuss the possibility of detecting SEP beams over 20 GeV.

2. A brief review of Bastille Day event

Bastille Day event (on July 14, 2000) is one of the most important solar energetic events in this solar cycle. Lots of observations and study results have been reported in a good many papers. A brief summary on the observational results of this event is of helps for our further discussion. Bastille Day event was associated with an X5.7/3B class parent solar flare produced in the optical coordinates N22W07. The flare really occupied an extended area along the solar equator. X-ray flare lasted from 10:03 to 10:43 UT with a peak at 10:24 UT. The onset of a type II radio burst, designating the starting of high energy phenomena in the flare and being thought to be close to the time of relativistic proton acceleration [9], happened at 10:12 UT with a maximum between 10:20 and 10:25 UT. Soon after that, the satellite-borne detector GOES observed a rapid increase of proton fluxes with energies larger than 10 MeV, 50 MeV and 100 MeV, respectively. Observed by the instrument on board of the Solar and Heliosphere Observatory SOHO/LASCO a full halo earth directed CME was developing during this event. On the ground, more than 20 NMs observed cosmic ray intensity increases ranging from 2% to 60%. The earliest onset time of NM increases was 10:30 UT. A small effect was recorded by the NM at the mountain Alma-Ata station (rigidity 6.7 GV), indicating solar protons up to 5.8 GeV.

Using the established technique and the well recognized geomagnetic field model [10,11], this GLE was modelled dynamically by Australian and Russian groups [12–15]. In their conclusions the following features were shown for the solar proton beam approaching the Earth: during the rising phase the spectrum was soft with a power law index of from -5 by initial to -7 by 11:00 UT; in the declining phase the spectrum softened and remained between -7 and -8 until 20.00 UT. From the pitch angle distribution it is seen that the particle arrival was anisotropic at the onset time, then it became increasingly isotropic, and after 1 h it turned to be highly anisotropic. The arrival direction (the pitch angle axis of symmetry) also rapidly changed with time. These features strong imply that SEPs arriving at the atmosphere are concentrated into a narrow sky cell and formed a beam.

3. Energy spectra

Taking data from the satellite-borne detector GOES-8, we constructed the proton energy spectra at Earth for $1\ \mathrm{MeV} < E < 500\ \mathrm{MeV}$ at several time intervals during 2000 July 14–16, shown in Fig. 1. For energy above 30 MeV except for first panel, the spectra were fitted by a power low function in rigidity

$$\mathrm{d}J_{\mathrm{p}}/\mathrm{d}E = A \times P^{-\delta} \tag{1}$$

where $\mathrm{d}J_{\mathrm{p}}/\mathrm{d}E$ is proton differential flux, A is a constant, P is proton rigidity and δ is spectral index. In Fig. 1 parameter P_1 represents constant A and P_2 represents spectral index δ. For all time intervals shown in Fig. 1, a good fit could be obtained by using a power law in rigidity, which was consistent with the diffusive coronal shock acceleration mechanism [16,17]. It is interesting that the spectral index of -2.7 before flare was same as that of galactic cosmic ray, indicating particle behavior of galactic cosmic ray during solar quite. It is evident that the spectrum changed with time in both amplitude and shape and there was a spectral "knee" occurring at $\sim$30 MeV. Since relativistic protons peaked in intensity earlier than the lower energy protons, the spectrum was hard at the rising phase and became soft in the declining phase.

In addition, using the flux deduced from NM observations [18], the spectrum at peak time 10:30 UT was extended to 3 GeV, as shown in Fig. 2. A power law fit was applied to this spectrum in energy range from 200 MeV to 3 GeV. Spectral index of -4.6 was obtained at this energy range, which was nearly consistent with modelling results mentioned in Section 2. For solar protons with energies higher than 3 GeV, because their intensity reached maximum earlier than the lower energy protons their spectral index should be more close to -4.6 according to the spectral index tendency obtained from modelling results. So we could extrapolate this spectrum to 40 GeV and calculated integrated fluxes for relativistic solar protons. For the purpose of comparison, we collected some solar proton fluxes in other big historical GLE events and constructed a solar proton integrated spectra shown in Fig. 3. These fluxes were obtained from various detectors such as satellite-borne detectors, NMs, ionization chambers (IC) and underground muon telescopes, or from modelling and theoretical calculation [7,19–23]. For Bastille