Proton spectrum of the 2005 January 20 solar flare

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Abstract An extreme solar cosmic ray event broke out on 2005 January 20. Not only is it the most intensive solar energetic particle (SEP) event, with >100 MeV particles measured by GOES satellite since 1986, but it has been the largest ground level enhancement (GLE) event recorded by the ground-based neutron monitors since 1956. This work presents the solar proton spectra for this event with data obtained by GOES in multiple energy channels. These spectra are well fitted by a modified power-law function. The spectral index of around −1 indicates that the January 20 event has a hard energy spectrum. Possible mechanisms for the acceleration of relativistic protons are discussed.

Key words spectrum, solar energetic particles, ground level enhancements, coronal mass ejections

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1 Introduction

On 2005 January 20 an extreme solar event was recorded by both the space-borne detectors and the ground-based instruments, such as GOES satellite and the worldwide network of neutron monitors. Just as other major solar eruptive events, this event was also associated with many violent solar activities, including large solar flare, strong radio emission and energetic coronal mass ejection (CME), etc. What significantly different about this event is that it happened to be in the descending phase of the 23rd cycle with the time period being very close to the minimum of solar activity. It is the most powerful solar proton event with relativistic energies seen in current solar cycle. This event may be compared by order of magnitude with other two greatest GLEs over the historical observation, the GLE 05 on February 23, 1956 and the GLE 42 on September 29, 1989[1]. The most outstanding feature of this event should be its very hard energy spectra and extremely short risetime[2—5], which marks it an unusual event for us to study the acceleration process of relativistic particles in big eruptive solar events. In this paper, we firstly give a brief review on the observation results from space-borne and ground-based detectors, next we examine the variation of energy spectra during the rise time in a few minutes, and finally we discuss its possible acceleration mechanisms.

2 Observations

On January 20, 2005, NOAA reported an X7.1/2B class solar flare in optical coordinates of N12W58 (AR10720). As shown in Fig. 1, the Transition Region and Coronal Explorer (TRACE)[6] observed the whole process of this flare in ultraviolet band with 1600 Åwavelength. It can be seen from the TRACE image in Fig. 1 that a very bright flare accompanying with a typical 'two-ribbon' structure had lasted for at least 13 minutes. After 8:28 UT this structure disappeared gradually and then connected with cooling loops.

Meanwhile, the soft X-ray (SXR) was first seen at 6:36 UT and the flux maximum of 7.1×10^{-4}W/m^2 observed by GOES satellite at 7:01 UT. As recorded by RHESSI, the hard X-ray (HXR) in energy between 0.8—7.0 MeV had a peak flux at 6:46 UT, the same as the one for the gamma ray burst with energy between 4 to 7 MeV[7]. The onset of metric Type II radio burst at 6:44 UT was recorded by several stations and registered in Solar Geophysical Data (SGD). Similarly, the Radio and Plasma Wave experiment (WAVES)[8] on the Wind spacecraft measured a decameter hectometer (DH) radio type II burst starting at about 6:45 UT, as shown in Fig. 2. On the other hand, the CME started to appear in LASCO field of view at 6:45 UT with its leading edge at 4.48R$_\odot$. Unfortunately, subsequent LASCO images were not available

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because the SOHO was affected by the 'snow storm' due to the arrival of solar energetic protons. Gopalswamy et al.[9] have evaluated the CME speed as high as 3675 km/s and the CME onset time is determined to be 6:33 UT according to the first set of LASCO data and EIT data. However, Simnett and Roelof, as well as Mewaldt et al have estimated the CME speed to be above 2500 km/s[3, 7]. With NOAA's GOES-11, peak flux of > 100 MeV proton was observed at 7:10 UT.

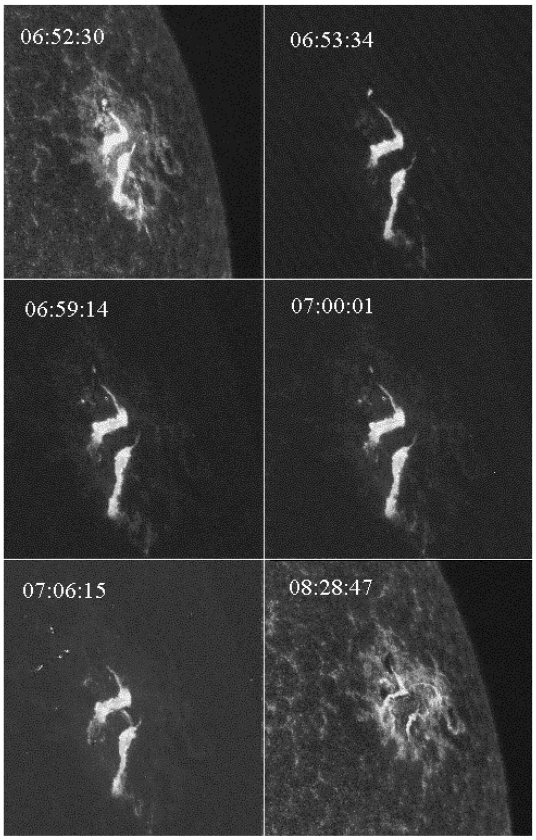

Fig. 1. Trace image in 1600 Åwavelength on January 20, 2005.

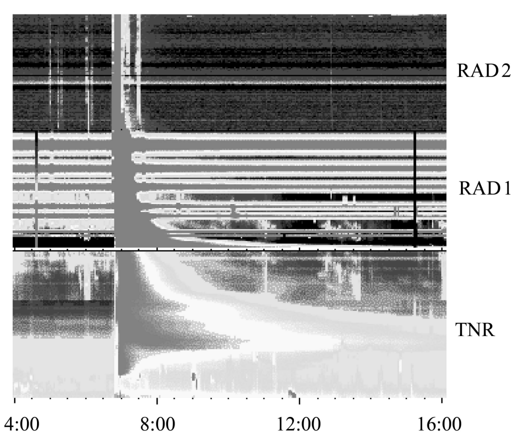

Fig. 2. Radio dynamic spectra observed by WAVES in three frequency windows on January 20, 2005.

On the Earth, more than 20 neutron monitors (NMs) have observed this solar cosmic ray event. Among them the South Pole Station had seen the highest amplitude of >5000% and the earliest sharp increase after 6:48 UT[10], as shown in Fig. 3. This figure also shows the observations of the other 5 NM stations, including Oulu, Moscow, McMurdo, Tixiebay and Kiel NM stations. The onset time at other NM stations came at later time but within about 9 minutes' reach. It should be mentioned that a small cosmic ray intensity variation was recorded by Yangbajing NM and solar neutron telescope between 6:53—6:54 UT, those detectors are located on the Tibet plateau with a geomagnetic vertical cutoff rigidity of 14.1 GV and an altitude of 4300 m a.s.l.[11]. It suggests that at least 13.2 GeV solar protons incident on the Earth had been accelerated in this event. On the other hand, an obvious muon ground level enhancement due to the high energy solar protons was observed by GRAND array[12], which can serve as another evidence that at least tens of GeV solar protons had been produced in this event.

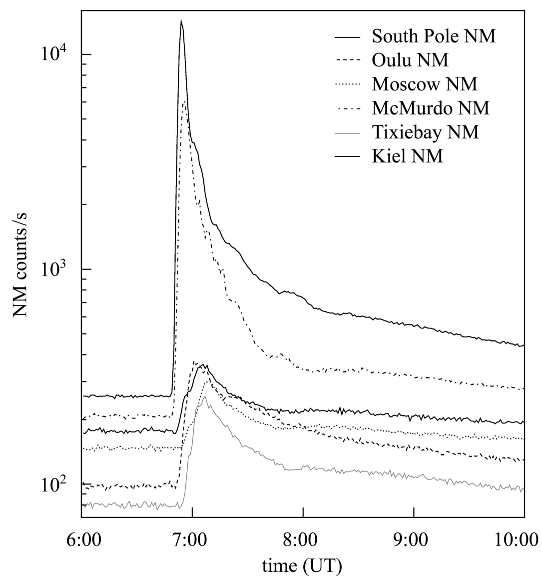

Fig. 3. Profiles of 6 NMs' counting rates for the GLE of January 20, 2005, including the South Pole, Oulu, Moscow, McMurdo, Tixiebay and Kiel NM stations.

3 Solar proton energy spectra

With the technique used in previous study[13, 14], we constructed the proton energy spectra for each five minutes bin from 6:50 UT to 7:15 UT, according to the data taken by the satellite-borne detector GOES-11. The spectra, with energy extending from 50 MeV to 500 MeV, were well fitted by a power-low function with an exponential cut-off, in form of $\mathrm{d}J_E/\mathrm{d}E = A \times E^{-\delta} \times \exp(-E/E_0)$. Here $\mathrm{d}J_E/\mathrm{d}E$ is the proton's differential spectrum, A is a constant, E is proton energy, δ is the spectral index, and E_0 is the cut-off energy from where the spectrum starts to become steeper. From Fig. 4 we can see that the solar proton flux has an obvious increase after 6:50 UT with a peak appearing at 7:05 UT and starts to recover after 7:10 UT for protons with energies of 50—160 MeV. Most solar protons with energies more than 350 MeV arrive at the Earth between 6:55—7:05 UT.

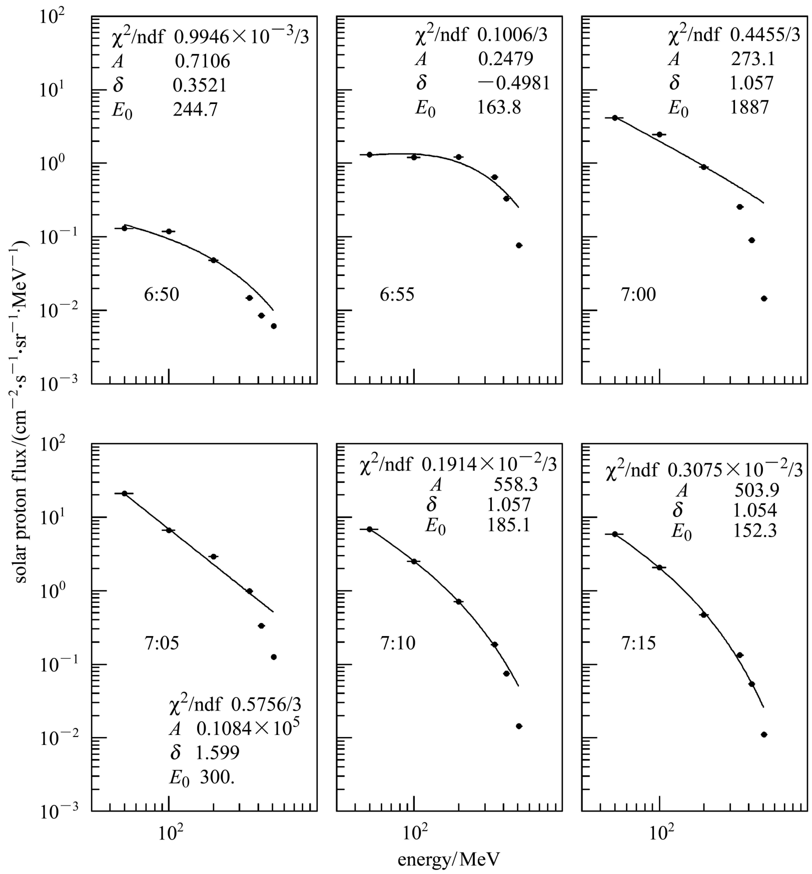

Fig. 4. Solar proton energy spectra at the Earth orbit for five minutes bins from 6:50 UT to 7:15 UT in GLE of January 20, 2005, based on GOES-11 data.

4 Discussion and conclusion

It is evident that the spectra changed with time in both amplitude and shape. There was a spectral "knee" occurring at about 300 MeV which was about ten times higher than that in the July 14, 2000 solar event[14]. This "knee" structure may be explained by the effect of velocity dispersion. Apparently, this effect is significant for the 300 MeV particles for this event. Higher energy particles above "knee" begin to leak out from the acceleration region so that the proton intensities can no longer sustain the growth of resonant waves, truncating the power-law behavior[15]. Because of the earlier arrival of the relativistic protons than the lower energy protons, the spectrum was hard at the rising phase and became soft in the declining phase.

There have been proposed various mechanisms in explaining the particle acceleration in the extreme solar events, mainly including the direct acceleration by DC electric fields in neutral current sheets, the diffusive shock acceleration at the bow shock of a CME, and the resonant wave-particle interaction (stochastic acceleration) initiated by MHD turbulence. In fact, these acceleration processes always co-exist in one event, and it is difficult to distinguish a diffusive shock acceleration from a stochastic acceleration. However, the dominated mechanism seems to be diffusive shock acceleration in this event owing to the power-law like energy spectra as can be seen in Fig. 4.

Flux of relativistic solar protons is well associated with the source position and energy of the flare, as well as its fast halo CME and radio type II emission[16]. A main reason for the hard spectrum and the fast rising time of this event should attribute to the fact that the flare location is very close to the "foot-point" of the interplanetary magnetic field line connecting the Earth and the Sun ($\sim 60^\circ$ West), besides other important contributions.

Although this extreme event also gives rise a large geomagnetic storm in two days[17], the intensity of the followed geomagnetic storm is not proportional to the flux of high energy solar particles, which will be specially studied later.

In conclusion, the solar proton energy spectra of January 20, 2005 solar event are well fitted by a power law function with exponential cut-off. The spectral index is close to −1 around the peak time at 7:00 UT and the spectral "knee" occurring at an energy as high as about 300 MeV. This event has the hardest energy spectrum and the fastest rising time among all those in solar cycle 23.

We are grateful to those who make various catalogs available on the internet, especially to GOES, TRACE, LASCO CME and WAVES, as well as the 6 NM stations (South Pole, Oulu, Moscow, McMurdo, Tixiebay and Kiel) for their data and image.

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