Simultaneous Detection of High-Energy Solar Neutrons and Protons at Chacaltaya Observatory on April 15, 2001

Y. MURAKI[1,9], Y. MATSUBARA[1], S. MASUDA[1], T. SAKO[1], S. SAKAKIBARA[1], K. WATANABE[1, 8], E. FLUECKIGER[2], R. BUETIKOFER[2], CHILINGARIAN[3], F. KAKIMOTO[4], T. TERASAWA[4], Y. TSUNESADA[4], H. TOKUNO[4], A. VELARDE[5],E.V. VASHENYK[6], T. SAKAI[7]

[1]*Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-8601, Japan*
[2]*Physikalisches Institute, University of Bern, CH-3012, Bern, Switzerland*
[3]*Yerevan Physics Institute, AM-375036, Yerevan, Armenia*
[4]*Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*
[5] *Instituto de Investigaciones Fisicas, Universidad Mayor de San Andres, Casilla 8635, La Paz, Bolivia*
[6] *Polar geophysical institute, Apatity 184200, Russia*
[7]*College of Industrial Technologies, Nihon University, Narashino, Japan*
[8]*Space Sciences Laboratory, University of California, Berkeley, CA 94720, U.S.A.*
[9]*Department of Physics, Konan University, Kobe 658-0072, Japan*

muraki@konan-u.ac.jp

Abstract: In association with the large solar flare of April 15th 2001, the Chacaltaya neutron monitor observed an 8.2 σ enhancement of the counting rate between 13:51 and 14:24 UT. Since the enhancement was observed from 11 minutes before the GLE, solar neutrons must be involved in this enhancement. The differential energy spectrum of solar neutrons can be expressed by a simple power law in energy with the index $\gamma = -4.0 \pm 1.0$. On the other hand, an integral energy spectrum of solar protons has been obtained in the energy range between 650 MeV and 12 GeV. The spectrum can also be expressed by a power law with the power index $\gamma = -2.75 \pm 0.15$. The flux of solar protons observed at Chacaltaya (at $\geqq$12 GeV) was already one order less than the flux of the galactic cosmic rays. It may be the first time to have the energy spectra of both high energy protons and neutrons simultaneously. Comparing with the *Yohkoh* Soft X-ray Telescope images with the observed particle time profiles, we can draw a picture on the particle acceleration mechanism as follows. By the loop-loop collisions, high speed plasma wind is generated. When the high speed plasma hits at the top of a magnetic loop, particles inside the loop may be accelerated by the collision process within a few minutes. This may be an origin of solar cosmic rays.

The solar neutron event observed by the Chacaltaya neutron monitor

In this paper we describe an interesting event detected in association with the solar flare of April 15, 2001. The position of the solar flare was at S20W85 and the intensity of X-rays measured by the *GOES* satellite was X14, a very strong flare. Ground level detectors observed a GLE (Ground Level Enhancement) in association with this flare [1-9].

The position of the Sun was suitable for the neutron detectors located at Chacaltaya, Bolivia and Gornergrat, Switzerland and possibly at Mt. Aragats, Armenia. The event was successfully observed by the *Yohkoh* spacecraft and very beautiful pictures were taken by Soft X-ray Telescope (SXT) and Hard X-ray Telescope (HXT). The Gamma-Ray Spectrometer (GRS) onboard *Yohkoh* also detected high-energy gamma-rays. Those observations provide important data for understanding the acceleration mechanism of ions to high energy.

In association with this gigantic solar flare, the Chacaltaya neutron monitor observed an 8.2 σ enhancement of the counting rate. The Chacaltaya observatory is located at the altitude of 5,250 m in Bolivia and includes a neutron monitor and a solar neutron counter. The latter has been in operation since 1992. The neutron monitor is standard 12NM64, composed of lead rings surrounded by polyethylene (total area is 13.1 m^2).

Figure 1 shows five minute time profiles observed by the Chacaltaya neutron monitor and plastic neutron counter. The data of the neutron monitor shows a daily variation and the minimum value was observed around at 11 am of the local time. In the data of the neutron monitor, we can see a clear peak starting from 13:51 UT. The 5 minute data of the neutron monitor tell us that the excess continued for more than 30 minutes. The statistical significance of the excess observed by the neutron monitor in the 33 minute value from 13:51 and 14:24 UT is 8.2 σ. Here the multiplication factor 1.65 of neutrons in the neutron monitor has been already taken account of.

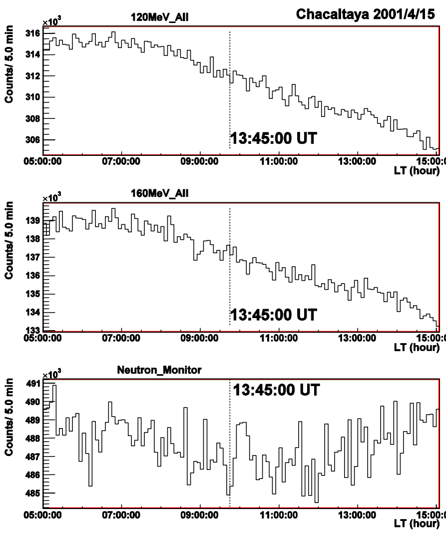

Figure 1: The Five minutes value observed by the Chacaltaya neutron counter(top and middle panel) and neutron monitor (bottom panel) in April 15, 2001. A clear enhancement was seen in the data starting from around 13:48 UT. The horizontal axis is presented by the local time in Bolivia.

For the Chacaltaya neutron monitor, the cutoff rigidity is estimated as 12.1 GV. The Chacaltaya neutron detectors did not see remarkable enhancement due to "traditional" GLE that enhances rapidly and decays slowly with more than two hours. This suggests that the low energy solar protons were rejected by the geomagnetic field and could not reach the Chacaltaya observatory at 5,250 m. We conclude therefore that the enhancement observed by the Chacaltaya neutron monitor between 13:50 and 14:02 UT must be mainly due to solar neutrons.

Differential Solar Neutron Spectrum

In this section we give results of the data analysis. We assume that ions were accelerated with the same time profile as gamma-rays as shown in Figure 2, i.e. the ions were accelerated from 13:45UT, and particle acceleration continued until 13:51UT, the end of strong emission of gamma-rays. Also we assume that the energy spectrum of solar neutrons can be expressed by a power law with indices γ from -3.0 to -7.0 [10].

As shown in Figure 3, a deviation from the fit can be seen around the peak at 14:05 UT. Therefore we have used a modified model and to fit to the observed data. In the solar flare of May 24, 1990, the arrival time of neutrons is clearly separated from the arrival time of protons [11, 12]. However during the flare of April 15, 2001, the time difference between arrival times of the neutrons and the protons was short.

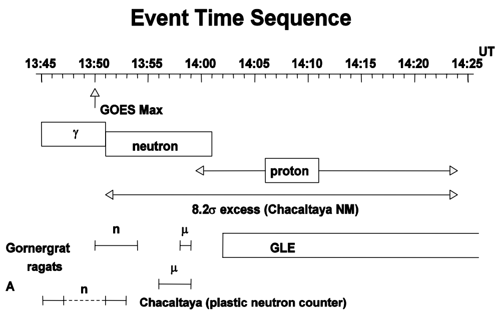

Figure 2: The event time profile observed by each detector. The major excesses are shown by the boxes. They correspond to the signals of gamma-rays, neutrons, protons and GLE. The time sequence of minor excesses of gamma-rays, neutrons, and muons as observed by the detectors located at Gornergrat, Mt. Atagats, and Chacaltaya is also shown together with major excesses. Each time corresponds to the time at the Earth.

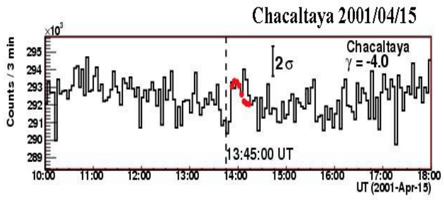

Figure 3: The results of the fitting to the 3 minute values of the Chacaltaya neutron monitor at the time interval between 13:45 and 14:12 UT. We have assumed that neutrons were produced with the same production time profile of gamma-rays a. In the time 14:06－14:12 UT, another peak can be recognized in the data of the neutron monitor. This second peak must be induced by the high-energy solar protons with Ep > 12 GeV.

Since the flare occurred at the west limb (W85), protons arrived at the Earth rapidly. This complicates the situation. We assume from 13:45 to 14:02 UT that only neutrons are involved in the enhancement observed at Chacaltaya. However after 14:02 UT, high energy protons may be included in the data. We attempted to separate the proton and neutron components in this time interval. The result of fitting the data between 13:51 and 14:06 UT is shown in Figure 3. When the power index of the differential spectrum takes the value $\gamma = -4.0$, the χ^2-value takes the minimum. According to the analysis of past neutron data by one of authors, the differential production spectrum of solar neutrons can be expressed by a power law with the index $\gamma = -3.0$ to -4.0 [10]. The present result is consistent with this analysis.

We obtained the proton flux after 14:06 UT by subtracting the neutron flux from the raw data. The procedure was as follows. The event time profile was fitted to the expected curve from the power law. The data points of Figure 3 represent the expected points for neutrons. The residuals from these plots were regarded as proton component. The number of protons is estimated as to be 2700 ± 600 events for six minutes during 14:06-14:12 UT. The statistical significance for the proton component is 4.5 σ while the statistical significance of neutron component is 5.8 σ. (As the multiplication factor of neutrons inside the neutron monitor, 1.65 is used.)

Integral Solar Proton Spectrum

Figure 4 represents the integral flux of solar protons for various GLEs. The data of the Easter event are presented by the black circle. From low energy to high energies, the four data points of the left side represent the value obtained by the GOES satellite, and then the neutron monitor data observed at Apatity, Jungfraujoch and Chacaltaya. It is impressive to know that protons were accelerated beyond 12 GeV and the flux can be expressed by a simple power law with an index of $\gamma = -2.75 \pm 0.15$ in the energy range between 650 MeV and 12 GeV (the energy range covered by the neutron monitors).

Here the error bars represent the statistical error only. The flux of the highest energy point observed at Chacaltaya is already one order less than the flux of the galactic cosmic rays. Since the altitude of the observatory is very high, the attenuation of solar protons was small, so that we could detect the signals.

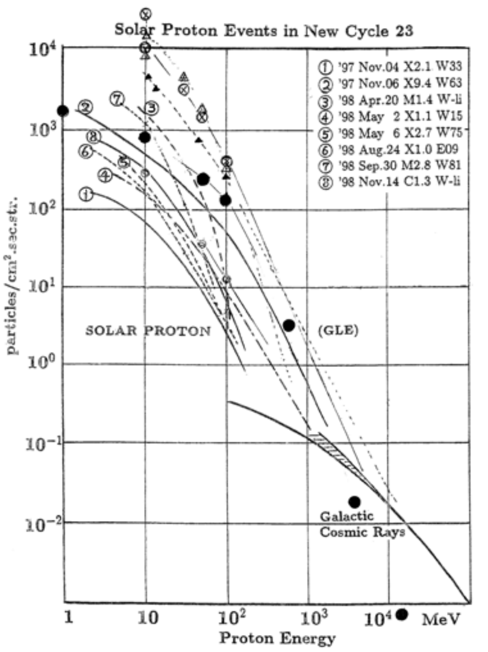

Figure 4: The integral flux of solar protons . The vertical axis represents in the unit of particles/ ($cm^2 \cdot sec \cdot sr$). The Easter event is presented by the black circles (●). The black triangles (▲) show the data observed in 1989 September 29th flare (X9.8). The round X mark corresponds to the data of the Bastille day event of 2000 (X5.7). The double circle (◎) and the open triangle (△) represent the data on April 18, 2001 flare (C2.2) and November 8, 2000 flare (M7.4) respectively.

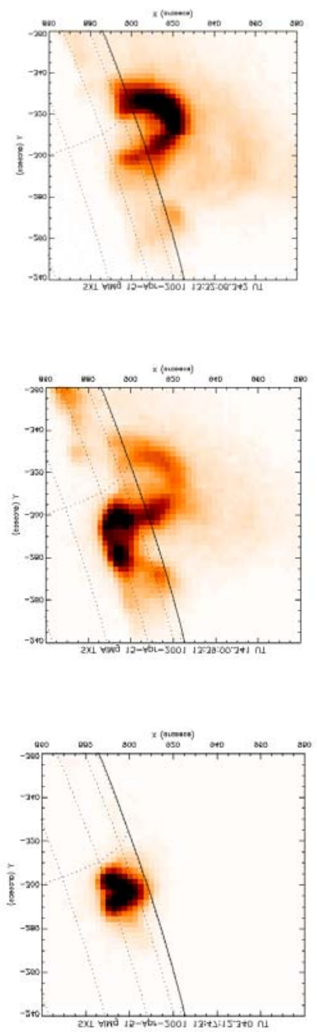

Figure 4: Dynamical features of the corona loops observed by the SXT telescopes of the *Yohkoh* in association with the large flare. From top to the bottom, the panel represents the dynamical motion of loops at C4 stage (top: 13:32 UT), M1 stage (middle: 13:39 UT) and X6 stage (bottom, 13:47 UT).

It may be the first time that the energy spectra of both high energy protons and neutrons are known simultaneously, though there are a number of reports on the energy spectra of GLEs (protons) [13, 14].

Summary of the Results

On April 15, 2001, a large solar flare was observed near the west limb of the Sun (the Easter flare). Its position was S20W85. In association with this flare solar neutrons were observed by the Chacaltaya neutron monitor.

They were produced contemporaneously with the gamma-ray lines at 13:45-13:51UT. We conclude that protons were accelerated during this period. The energy spectra of the emitted protons and neutrons follow a power law with indices $\g $\gamma = -2.75 \pm 0.15$ and $\gamma = -4.0 \pm 1.0$ (differential) respectively.

Soft X-ray images of the flare by the *Yohkoh* satellite indicate that proton acceleration probably occurred when the foot of a magnetic loop collided with the other magnetic loop. Plasma particles inside the loop may be accelerated by a shock acceleration process, in which plasma particles attain high energies in a few minutes by interacting with high-speed wind.

The flux of high-energy protons with energies exceeding 12 GeV was an order of magnitude less than the flux of galactic cosmic rays. This ren dered their detection by the GLE neutron monitor a difficult task. Such detection is probably only possible in extremely large solar flares, such as the one observed in September 29, 1989.

The authors thank Prof. P. Evenson for valuable discussions.

References

[1] E.G. Cordaro et al., Proc. 27th ICRC, (2001) 3368.
[2] A.J. Tylka et al., Proc. 28th ICRC, 6 (2003) 3305.
[3] W.F. Dietrich et al, Proc. 28th ICRC, 6 (2003) 3291.
[4] L.I. Miroshnichenko, Proc. 28th ICRC, 6 (2003) 3321.
[5] J.W. Bieber et al., Proc. 28th ICRC, 6 (2003) 3397.
[6] E.V. Vashenyuk et al., Proc. 28th ICRC, 6 (2003) 3401.
[7] S.W. Kahler et al., Proc. 28th ICRC, 6 (2003) 3415.
[8]C. D'Andrea et al, Proc. 28th ICRC, 6 (2003) 3423.
[9] S.N. Karpov et al., in: Proc. 28th ICRC, 6 (2003) 3427.
[10] K. Watanabe et al., Astrophys. J., 592 (2003) 590. K. Watanabe et al., Astrophys. J., 636 (2006) 1135.
[11] H. Debrunner, J.A. Lockwood, J. Ryan, Astrophys. J., 409 (1993) 822.
[12] Y. Muraki, S. Shibata, AIP Conf.,Proc,374, AIP, (1996) 256.
[13] L.I. Dorman, in: Cosmic Rays - Variations and Space Explorations, North-Holland Publishing Company (1974). L.I. Dorman, in: Cosmic rays in the earth's atmosphere and underground, Kluwar Academic Publishers, London (2004).
[14] L.I. Miroshnichenko, Solar Cosmic Rays, Kulwar Academic Publishers (2001).