Detection of Solar Neutrons and Protons by Ground Level Detectors

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***Abstract*—In association with the large solar flare of April 15th 2001, the Chacaltaya neutron monitor observed an 8σ enhancement of the counting rate. Since the enhancement was observed from 14 minute before the GLE, we think that solar neutrons made this enhancement. At the same time the detectors located at Gornergrat and Mt. Aragats observed enhancements. The high-energy protons that arrived on the Earth faster than the main stream of particles, the well-known GLE component, must induce those enhancements.**

I. Introduction

SINCE the discovery of solar neutrons by the detector onboard the SMM satellite [1] and detectors located on high mountains [2]-[4], almost 25 years have passed. Initially detection of solar neutrons was a very rare event. At that time, we did not know whether or not solar neutrons were produced impulsively or produced by gradually accelerated ions. Even today, it is not so clear whether those ions are accelerated at the same time as electrons. We cannot say that we understand well the particle acceleration mechanism at the Sun, for example whether they are accelerated by shock mechanism [5] or by a DC mechanism [6].

Owing to our effort to collect more solar neutron events, at least parts of some questions have been understood. The ions must be accelerated simultaneously to high energies with electrons, because when solar neutron events are observed, hard X-rays are detected [7],[8]. Strong emission of hard X-rays is observed for a few minutes. Therefore it is natural to conclude that ions are also accelerated to high energy within a few minutes.

However exceptional cases are sometimes seen. Strong emission of neutrons from the Sun was observed, but at different time from when strong emission of hard X-rays was seen. As an example of such an event, we can point to an event observed by the solar neutron telescope in Tibet on September 24, 2001 [9]. Another example is the event of September 7, 2005 observed by the solar neutron detectors located at Chacaltaya and Mexico [10],[11]. We cannot understand well the reason why the emission of line gamma-rays was weak. Thus, still there remain several important and interesting questions regarding solar neutron physics. We have not yet fully understood these phenomena and hence we must continue the observation of solar neutrons through solar cycle 24.

In this paper we introduce another interesting event detected in association with the solar flare of April 15, 2001. The position of the Sun was suitable for the neutron detectors located at Chacaltaya, Bolivia and Gornergrat, Switzerland and possibly at Mt Aragats. The event was successfully observed by the Yohkoh spacecraft and very beautiful pictures were taken by SXT and hard X-ray telescopes. The Gamma-Ray Spectrometer onboard Yohkoh also detected high-energy gamma rays. Those data provide us an important hint for understanding the acceleration mechanism of ions to high energy. In this paper we discuss novel features of the event.

II. The Ability of Detectors to Identify Solar Neutrons

On April 15, 2001 a strong flare was observed at the west limb of the solar surface specifically at the position S20W85. The intensity of X-rays measured by the GOES satellite was X14, a very strong flare. In association with this gigantic solar flare, the Chacaltaya neutron monitor observed an 8σ enhancement of the counting rate. We will discuss the observation data in comparison with other observation results observed by using the Gornergrat and Mt. Aragats detectors in this paper. However before introduction of the event, at first we will explain the characteristics of each detector.

A. *The Chacaltaya neutron monitor*

The Chacaltaya observatory is located at the altitude of 5,250m in Bolivia containing a neutron monitor and a solar neutron detector. The solar neutron detector has been in operation since 1992. The neutron monitor is standard 11NM64, composed of lead rings surrounded by polyethylene. "High energy" (about 10-1000 MeV) neutrons enter the lead target, interacting with the lead nuclei. Then "medium energy"

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neutrons (1-20 MeV) are produced by the evaporation process of the lead nuclei. Those medium energy neutrons collide with the hydrogen atoms in the paraffin and reduce their momentum by the collisions. Then these "low energy" neutrons can enter into the BF_3 counter (a proportional counter) located at the center of the neutron monitor inside the lead ring. Then by the collision with the Boron of the counter gas, $B^{10} + n \rightarrow \alpha + Li^7$, an alpha particle is produced and the proportional counter can register the entrance of a neutron. Since the detector has been prepared to be sensitive only to $Z \geqq 2e$ particles, the neutron monitor does not record the minimum ionizing particles such as relativistic muons and electrons. So neutron monitor is a quite background free detector for the secondary cosmic rays like muons and electrons and has sensitivity to the hadronic components like neutrons and protons. The detection efficiency was calculated as 10-40% by Hatton [12] and Clem et al. [13] (it depends on the energy) and calibrated with use of the neutron beam from the accelerator [14].

B. The Chacaltaya scintillation counter

The Chacaltaya scintillation counter is composed of $4m^2$ plastic scintillator with a thickness of 40cm covered with anti-counters so that the detector can separate neutral particles from charged particles like muons, electrons and protons. Photons can penetrate the anti-counters and be converted into electron positron pairs inside the plastic scintillator. Those photons will become the background for the detection of neutrons. The detection efficiency of a scintillator based neutron detector was calibrated by the accelerator beam and it turns out to be 40% (the efficiency is 10% for every 10cm thickness of the scintillator).

A good comparison of it with the Chacaltaya neutron monitor can be made by use of the real event on September 7th 2005 [11]. In Figure 1, we plot the neutron event detected at Chacaltaya by both neutron monitor and neutron detector based on the plastic scintillator. In this flare, the Chacaltaya neutron monitor counted 95,000 neutrons, while the Chacaltaya scintillation detector counted 17,000 events for E_n > 40MeV, 9,000 events for E_n > 80 MeV, 3,000 events for E_n > 160 MeV and 450 events for E_n > 240 MeV. They are 17.8, 9.5, 3.15 and 0.47% of the flux detected by the neutron monitor, reflecting the energy spectrum of the arriving neutrons. It is worthwhile to mention here that the neutron monitor cannot determine the energy of neutrons by itself while the neutron detector can measure the minimum energy of arriving neutrons because those neutrons collide with carbon or hydrogen targets in the plastic scintillator and produce proton tracks. The energy of the protons can be measured from the track length, i.e., it is proportional to the intensity of the light.

C. The Swiss neutron telescope and the Mt. Aragatz neutron detector

The Swiss neutron telescope is composed of plastic scintillators with a thickness of 40cm. The anti-counters made of cylindrical proportional counters surround them. So approximately 20% of charged particles (mainly muons) enter inside the scintillator and make a background for the detection of neutrons. Details of the detector were reported by Buetikofer et al [15]. The detector identifies the arrival directions of solar neutrons classified into 5 directions from the north to the south.

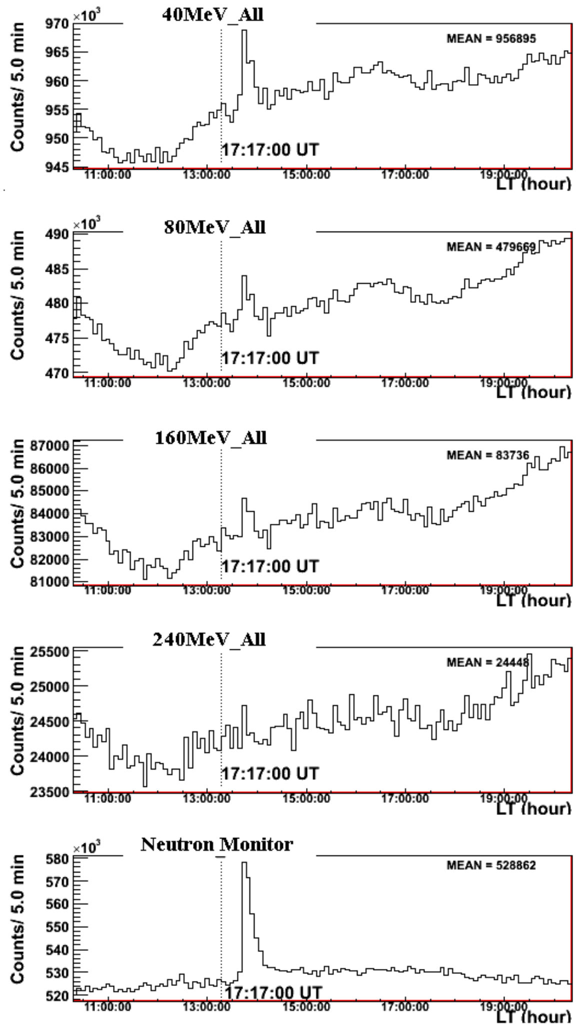

Figure 1. The 5 minutes value observed by the solar neutron telescope and the neutron monitor located at Chacaltaya on September 7, 2005 event. Both plastic neutron detector and neutron monitor observed clear signals in this event.

The Armenian scintillation detector has a similar shape to the Chacaltaya plastic scintillation counter but the thickness of the plastic scintillator is 60 cm and the anti-counter is located on the top of the detector. Detail can be found in another paper [11].

D. The Yohkoh HXT, SXT and GRS detectors

The Yohkoh Soft X-ray Telescope, SXT, can see images of solar flares. The dynamic motion of coronal loops by the Yohkoh SXT has been reported elsewhere [17]. In this paper the data of the SXT are used to understand the acceleration mechanism of particles. The Yohkoh SXT is sensitive to X-rays in the energy range from 0.25 keV to 4.0 keV [18]. When electrons are accelerated to high energies, X-rays with shorter wavelengths are emitted. The Yohkoh Hard X-ray Telescope, HXT has four windows for the different wavelength from 10 keV to 100 keV [19]. Since this flare occurred at the west limb of the Sun, the HXT detector has obtained beautiful pictures of X-rays.

The Yohkoh satellite carried the Gamma-Ray Spectrometer, GRS. The detector could record gamma rays within the energy range between 270 keV and 100 MeV [20]. High-energy photons are emitted by high-energy electrons through Bremsstrahlung and the line gamma rays are emitted by mechanisms inherent to the ions. Within them, the 2.223MeV and 4.44MeV line gamma rays are well known to originate from the neutron capture line and the de-excited line of the carbon target in the solar atmosphere.

III. THE EVENT OBSERVED BY THE CHACALTAYA NEUTRON MONITOR AND OTHER GROUND LEVEL DETECTOR

Here we introduce the general features observed by the Chacaltaya neutron monitor. According to the observation of the GOES satellite, the flare started at 13:19 UT and reached the maximum at 13:50 UT. However as shown in Figure 2, the flare increased the intensity by three steps from C4 (at 13:28UT), M1 (at 13:40UT) and X10 (at 13:48UT). The X-rays were emitted abruptly from M4 to X10 within two minutes between 13:45 and 13:48UT. The Yohkoh satellite could observe the flare from the initial stage at 13:22UT through the maximum until 13:56UT. The shadows shown in Figure 2 represent the South Atlantic Anomaly of the Yohkoh satellite and the shadow of the Earth for the Yohkoh orbit.

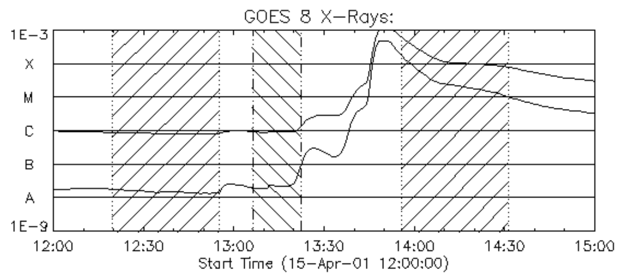

Figure 2. The X-ray intensity time profile observed by the GOES satellite. The X-ray intensity increased by 3 steps, at 13:28UT (C4), 13:40UT (M1), and 13:48 (X10) UT. The shadows represent the South Atlantic anomaly (negative slope) and shadow of the Earth (positive slope) for the Yohkoh satellite respectively.

Figure 3 represents the 5 minutes time profiles observed by the Chacaltaya neutron monitor and the plastic neutron detector. The Chacaltaya neutron detector is composed of plastic scintillator with a thickness of 40 cm. In the data of the neutron monitor, we can see a clear peak starting from 13:48UT. The time coincides with the time when the flare reached the intensity over X10. However in the data of the plastic neutron detector, only marginal (2 σ level) enhancements were seen. The 5 minute data of the neutron monitor tell us that the excess continued for more than 20 minutes, while in the data of the plastic scintillator only the excess in the highest energy channel (E_n > 240MeV) was recorded. The background might mask the low energy part of the signal. We will discuss whether this peak observed by the neutron monitor arose from solar neutrons or not. The statistical significance of the excess is 8σ and it is with great confidence an enhancement.

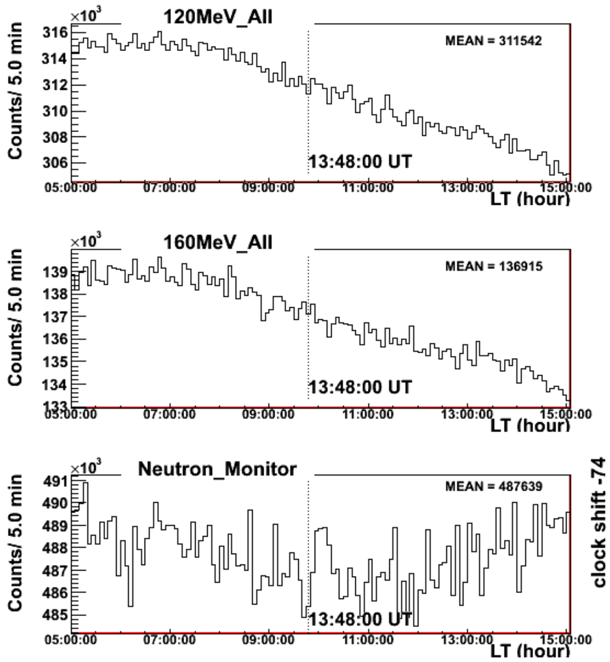

Figure 3. Five minutes value observed by the Chacaltaya plastic neutron detector (top and middle panel) and by the neutron monitor (bottom panel) in April 15, 2001. A clear enhancement was seen in the data of the neutron monitor starting from around 13:48UT.

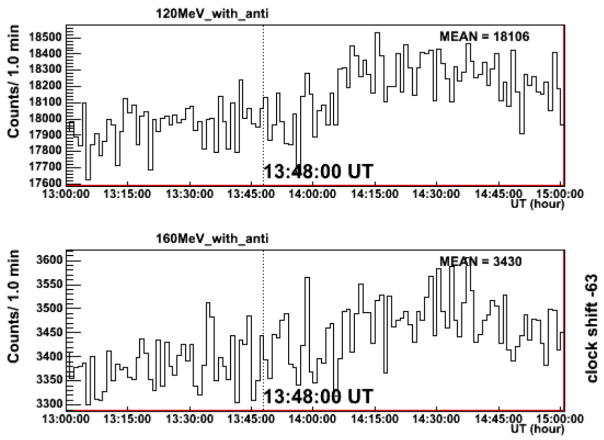

Figure 4. The time profile of the counting rate of the neutral channel observed of the Gornergrat neutron telescope for the event in April 15, 2001. Top panel represents the intensity of neutral particles beyond 120 MeV and bottom panel represents the intensity beyond 160 MeV. There seem few spikes before 14:00UT.

In Figure 4, we plot the time profile of the counting rate of the neutron channel observed by the Gornergrat neutron telescope. As can be seen from Figure 4, the increase of the counting rate started at 14:02UT. The Oulu neutron monitor recorded a GLE at the same time. The Chacaltaya neutron detector did not see any enhancement due to the GLE. The atmospheric depth to the Sun was 719g/cm^2 and 808 g/cm^2 at

Chacaltaya and Gornergrat respectively but at Mt. Aragats it was 1006 g/cm^2. According to our empirical law, it is impossible to see signals of solar neutrons in current detectors when the atmospheric depth is deeper than 800 g/cm^2 [21]. Therefore we conclude that the enhancement observed by the Chacaltaya neutron monitor must be due to solar neutrons and definitely not the GLE.

Next we discuss small bumps observed with less statistical significance. It is very interesting that two detectors located at the different longitude observed similar enhancements at 13:58-13:59UT (at Gornergrat, 2.8σ) and 13:57-13:59UT (at Mt. Aragatz detector, 3.5σ . See Figure 5.)

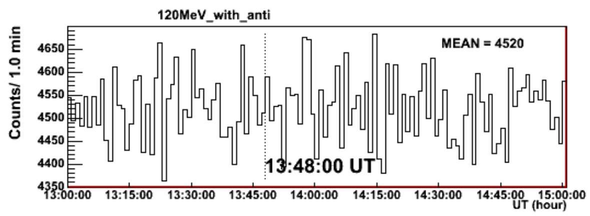

Figure 5. The time profile of the counting rate of the neutral channel observed by the Mt. Aragats neutron detector. A few minutes before the GLE that was observed by the Oulu neutron monitor (13:52UT), an enhancement was observed.

Those enhancements might be induced by the high energy protons that arrived on the Earth faster than the main stream of particles, the well known GLE component. In other words, high-energy component must arrive on the Earth before 14:02UT, however due to the strong background by the galactic cosmic rays, they were below the detection limit of the detectors. Since the neutron telescope has sensitivity to high energy muons by chance, the muons produced by high-energy protons beyond Ep> 10 GeV must be observed by these two detectors.

The Gornergrat detector observed also a small enhancement (3.1σ) at 13:50-13:54UT at the highest energy channel (E_n> 160 MeV). We believe that solar neutrons must produce this enhancement. Since the atmospheric depth for Gornergrat was deeper than Chacaltaya by about 100gr, the attenuation of solar neutrons was large and a clear signal was diluted by the background. The Chacaltaya scintillation detector observed minor excesses at 13:44-13:46 and 13:50-13:52 UT. The level of statistical significance was 2σ . So we could not say for certain that the plastic neutron detector did see neutron signals, but we can have a good scenario for this event, namely that these minor enhancements were produced by the highest energy solar neutrons produced by this flare. The emission of these neutrons must start at 13:44-13:45UT. The time coincided with the start time of emission of hard X-rays.

Since the intensity of neutrons was one order of magnitude less than that of September 7 flares of 2005, the background masked the signals of other energies. This interpretation seems for us quite natural and consistent with the data obtained by the worldwide solar neutron telescope (SONTEL) and the neutron monitor.

IV. BEAUTIFUL IMAGES OBSERVED BY THE YOHKOH IN THIS FLARE

Figure 6 represents the time profile of the HXT, where the emission of the hard X-rays started at 13:44UT. The emission was quite notable at 13:45UT and at 13:46:30UT, but the intensity had already passed the first peak. Second and the third peaks can be seen at 13:47:45UT and 13:49UT. The hardest channel H of the region of 50-100 keV shows a quite spiky structure, so the particle acceleration occurred during 6 minute from 13:44UT to 13:51UT. The dominant emission of hard X-rays can be seen at three points of the loop, the foot points and at the top point. It shows a typical Masuda flare as shown in Fig. 7 (bottom right panel) [22]. However when we look the flare from the initial stage, an interesting fact has been found.

In Figure 7, a sketch of the dynamical behaviours of the loop is shown. This feature was taken by using the Yohkoh SXT telescope. Figure 7 tells us that the loop used for the acceleration of particles is different from each stage and it is different from C4, M1 and X10 levels. The acceleration occurred in different loops and reached the maximum intensity as X14 in this event.

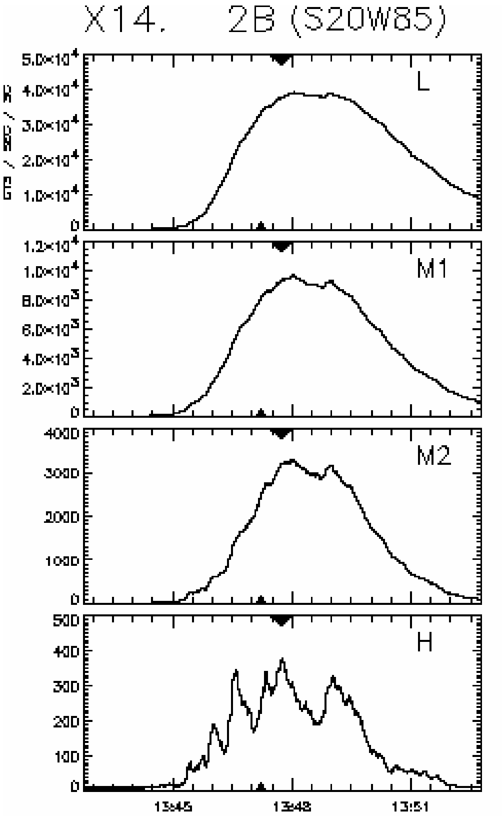

Figure 6. The time profile of the Yohkoh HXT, where the emission of the hard X-ray started at 13:44UT on April 15, 2001. A spiky feature of the X-ray emission can be seen in the highest channel H. The corresponding energies for each channel is 10-30 keV for L, 20-40keV for M1, 30-60 keV for M2 and 50-100 keV for H.

It is interesting to note that like in man-made accelerators, the Sun accelerates particles in different loops (rings). At

CERN, particles are accelerated at first by using the linear accelerator (this corresponds to the heating process at the Sun), then particles are injected into the Proton Synchrotron and accelerated to 24 GeV (the heated plasma is accelerated to the level of C4 at the Sun), then injected to the SPS ring up to 450 GeV (M1 level at this flare). In 2008, these particles will be

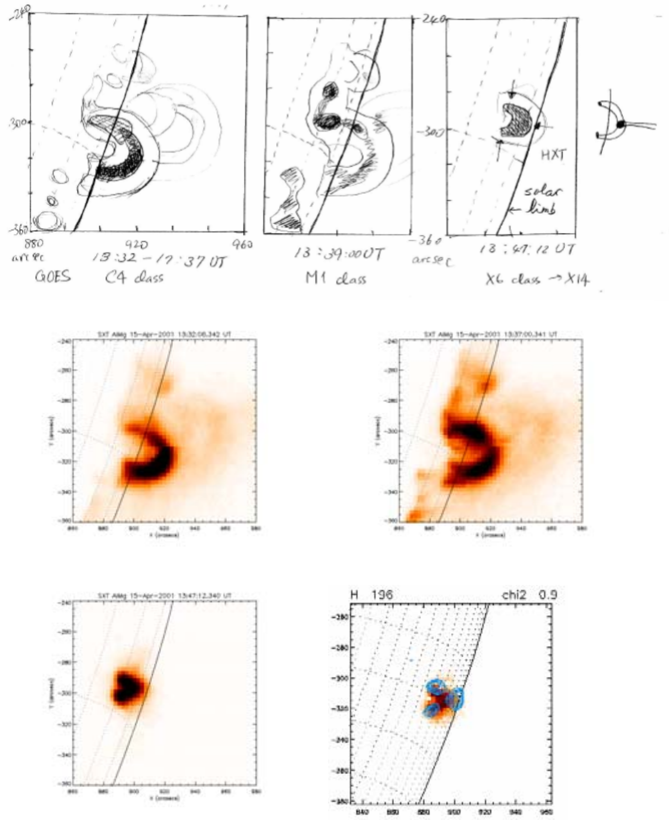

Figure 7. Dynamical features of the corona loops observed by the SXT telescope of the Yohkoh in association the large flare. The top panel shows the sketch of the dynamical motion of loops at C4 stage (left, 13:32-37UT), M1 stage (middle, 13:39UT) and X6 to X14 stage (right, 13:47UT) respectively. The middle panel shows the SXT images for C4 and M1 stages and the bottom panel shows for the X6 stage. In the right side of the bottom panel, the positions of the hard X-rays emission are drawn by the blue circle.

accelerated further into high-energies by using the LHC ring up to 7 TeV (X10 at the Sun). When we consider the common acceleration feature between the Sun and human made accelerator, we gain some intuition into the particle acceleration mechanism at the solar surface.

This three-step acceleration example is not a universal feature at the Sun. In most large flares, the flare abruptly and impulsively increases its intensity within a few minutes. We find another good example of the three-step acceleration in the flare of November 28, 1998. The further study of this type of particle acceleration may resolve the particle acceleration mechanism on the solar surface.

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