

## Analysis of Solar Gamma Rays and Solar Neutrons detected on March 7<sup>th</sup> and September 25<sup>th</sup> of 2011 by Ground Level Neutron Telescopes, SEDA-FIB and FERMI-LAT

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### abstract

At the 33<sup>rd</sup> ICRC, we reported the possible detection of solar gamma rays by a ground level detector and later re-examined this event. On March 7, 2011, the solar neutron telescope (SNT) located at Mt. Sierra Negra, Mexico (4,600 m) observed enhancements of the counting rate from 19:49 to 20:02 UT and from 20:50 to 21:01 UT. The statistical significance was  $9.7\sigma$  and  $8.5\sigma$ , respectively. This paper discusses the possibility of using this mountain detector to detect solar gamma rays.

In association with this event, the solar neutron detector SEDA-FIB onboard the International Space Station has also detected solar neutrons with a statistical significance of  $7.5\sigma$ . The FERMI-LAT detector also observed high-energy gamma rays from this flare with a statistical significance of  $6.7\sigma$ . We thus attempted to make a unified model to explain this data. We also report on another candidate for solar gamma rays detected on September 25<sup>th</sup>, 2011 by the SNT located in Tibet (4,300 m) from 04:37 to 04:47 UT with a statistical significance of  $8.0\sigma$  (by the Li-Ma method).

### 1. Introduction

The solar flare observed at 19:48 UT on March 7, 2011 may be one of the most important flares observed in Solar Cycle 24. Although the intensity of the flare measured by the GOES satellite was moderate, M3.7, the event has already provided us with important information. From this information, we were able to point out an emission of long-lasting, high-energy gamma rays detected by the FERMI-LAT satellite. This emission continued for 14 hours and high-energy

gamma rays with an energy of  $\sim 4\text{GeV}$  were recorded.<sup>[1]</sup> Another fact is that this marked the first detection of solar neutrons in Solar Cycle 24 using the solar neutron telescope (SEDA-FIB) onboard the International Space Station (ISS).<sup>[2]</sup> Conversely, a solar neutron telescope (SNT) located at Mt. Sierra Negra in Mexico observed two enhancements of the counting rate during the flare.<sup>[3]</sup> The Mt. Sierra Negra observatory is located at an altitude of 4,600 m a.s.l. In this paper, we will discuss whether these observation results may be explained by a unified model.

This paper is organized as follows: The next section introduces the data observed by referred instruments. Sections 3 and 4 describe our interpretations that could explain the data consistently. In section 5, we summarize the results.

## 2. Observational Data

Here we present the space environment data obtained from around 19:30 to 21:00 UT on March 7, 2011. Data were obtained by five different satellites and one ground-based detector: GOES, RHESSI, FERMI-GBM,<sup>[4]</sup> FERMI-LAT,<sup>[5]</sup> and SEDA-FIB, as well as the SDO and SNT at Mt. Sierra Negra, Mexico. **Figure 1** presents the time lines of the different data.

### 1. GOES data

The soft X-ray sensors on the GOES satellite detected a flare that started at 19:43 UT and reached its maximum at 20:12 UT with magnitude M3.7. The flare position was identified at about N23W50 on the solar surface in Active Region 11164.

### 2. RHESSI satellite

The RHESSI satellite also observed this flare from 19:27 to 20:08 UT. The emission of hard X-rays with 25-300 keV started at  $\sim 19:47$  UT and peaked at 20:00 UT. Two-dimensional plots are made for the times of maxima at 19:57 UT and 20:01 UT using the hard X-ray data of the RHESSI satellite. The peak positions of hard X-rays and soft gamma rays are estimated using the RHESSI data at the solar coordinates of (625", 560") for 19:57 UT and (610", 560") for 20:01 UT (indicated by the circle in Figure 3).

### 3. FERMI-GBM results

The FERMI satellite involves two main detectors (GBM and LAT). The GBM monitors gamma-ray bursts in the range of X-rays between 6 and 300 keV.<sup>[6]</sup> The FERMI-GBM detector observed the Sun from 20:02 to 20:40 UT on March 7, 2011. The intensity of hard X-rays in the range of 100-300 keV was 2,000 counts per second at 20:02 UT for just after the first peak, and in the second peak at 20:38 UT, a counting rate of  $\sim 800$  counts per seconds was recorded. Unfortunately, the detectors failed to observe the first impulsive phase of the flare. When comparing the time profile of the GBM with that of GOES, however, a clear difference can be recognized. The observation using soft X-rays only showed one peak in contrast, the observation using hard X-rays clearly showed a second peak at  $\sim 20:38$  UT.<sup>[6]</sup>

### 4. FERMI-LAT results

The high-energy gamma-ray detector FERMI-LAT observed the flare from 20:15 to 20:40 UT. High-energy gamma rays with a peak intensity at 200 MeV were detected. The highest gamma rays reached  $E_\gamma \sim 4$  GeV. The emission of gamma rays continued for 14 hours, the details of which have been published.<sup>[1]</sup> The detector failed to detect the impulsive phases of the flare.

### 5. SEDA-FIB results on the ISS

The SEDA-AP is a neutron sensor onboard the ISS. The sensor can measure the energy and arrival direction of neutrons. Details may be found in the references.<sup>[7-10]</sup> The production time may be estimated using information on the energy of neutron-induced protons in the sensor. **Figure 2** shows the energy spectra of solar neutrons. The most probable production time of neutrons is estimated to be around 19:58 UT for the first peak and 20:37 UT for the second peak. The SEDA-FIB also failed to detect the impulsive phase of the first peak. This

is because the ISS passed over the night area of the Earth until 20:02 UT.

#### 6. SDO satellite

The Solar Dynamics Observatory observes the Sun by means of ultra-violet telescopes over different wavelengths. The SDO satellite successfully observed the emission of a Coronal Mass Ejection (CME) associated with this flare from the start time of emissions. Thus, the satellite not only observed the start of the CME but also its development from the start time of an impulsive flare at ~19:47 UT.<sup>[11]</sup>

**Figure 3** shows several images taken at 19:47 UT, 19:58 UT, 20:37 UT, and 20:50 UT by the SDO/AIA telescope. The 30.4nm line emission is produced by the helium ions. The intensive emission area of hard X-rays determined by the RHESSI observation is circled in the image. The time of 19:47 UT corresponds to the start time of the magnetic loop forming the CME, while 20:50 UT corresponds to the peak time of the counting rate detected by the SNT at Mt. Sierra Negra. Thus, 19:58 UT and 20:37 UT are the estimated solar neutron production times.

#### 7. Solar Neutron Telescope at Mt. Sierra Negra and Tibet

**Figure 4** shows the time profile of the L1 channel between 19:00 and 21:30 UT as observed by the SNT at Sierra Negra<sup>[12]</sup>. Two clear enhancements from 19:49 to 20:02UT and from 20:50 to 21:01UT can be recognized. **Figure 5** shows the time profile of the neutron channel. The N1/L1 is 0.16~0.40, depending on the background level of the N1 channel. It sharply contrasts from the solar neutron event observed on September 7th, 2005 by the same detector<sup>[13]</sup>. The N1/L1 ratio was ~7 in the event.

We found a similar event in observation data obtained by the SNT located in Tibet (4,300 m) on September 25th, 2011, following the M7.4 flare at 04:33 UT.<sup>[14]</sup> **Figure 6** (left) shows the time profile of L3 channel between 04:00 and 07:00UT. In comparison with the neutron channel of  $E_n > 40\text{MeV}$  (**Figure 6** right), a clear enhancement is recognized. The statistical significance is  $5.2\sigma$  by the Li-Ma method. **Figure 7** presents the time profile of the neutron monitor located in Tibet at the same time. **Figure 8** shows the SEDA-FIB data. **Figure 9** represents the ratio between L3 and n40 ( $E_n > 40\text{MeV}$ ) channels.

### 3. Comparison of Observed Intensities between SEDA and SNT

At the time of the flare, the SNT at Mt. Sierra Negra (SN-SNT) and the SEDA-FIB recorded two enhancements.<sup>[14]</sup> This raises the question of whether both enhancements were produced in association with the M3.7 flare. The enhancements recorded by the SNT were only observed by the L1 channel that consists of proportional counters located just under the scintillator. Except for a minor enhancement of the anti-counter, a positive signal of neutrons was not recorded. A similar trend can be recognized in the data observed at Tibet. Therefore, these enhancements recorded by the SNTs must have been produced by gamma rays. In such case, we have estimated the intensity of gamma rays that entered the top of the atmosphere.

The counting rate of the L1 channel at SN-SNT was estimated as 152 counts/m<sup>2</sup>/min. and 145 counts/m<sup>2</sup>/min. for the first peak and second peak, respectively. Monte Carlo (MC) results were used to estimate the incident flux at the top of the atmosphere. According to the MC calculation, the attenuation is estimated as 0.1 for photons with energy of  $E = 1\text{ GeV}$ , 0.01 for photons of 200MeV, 0.003 for 100MeV and 0.001 for photons with energy of 30 MeV. Then the flux at the top of the atmosphere is approximately estimated to be 150,000 counts/m<sup>2</sup>/min.

The flux of solar neutrons with  $E_n > 30\text{ MeV}$  is conversely estimated as follows: From Fig. 2 (left), the number of neutrons after “decay correction” is estimated as 149 counts/100 cm<sup>2</sup> or 14,900/m<sup>2</sup>. Given the SEDA-FIB sensor’s efficiency in detecting neutrons (estimated at 2%), the net value at the top of the atmosphere after decay correction turns out to be  $7.5 \times 10^5$  counts/m<sup>2</sup>. If these neutrons were emitted during seven minutes, the intensive hard-X ray emission time, we

could compare both values. Then we would find that both are of the same order at a ratio of about 1.7 (= neutrons/gamma rays). We have checked these values obtained by the recent MC calculation based on GEANT 4<sup>[15]</sup>.

Using the MC calculation to estimate the flux in the direction toward the Earth, we assumed an opening angle of 57 degrees between the vertical direction and the direction toward the Earth. The MC calculation predicts the ratio to be  $\sim$ one at  $E_{n \text{ or } \gamma} > 30$  MeV in case the accelerated protons have the power index of -5. Although the SEDA did not observe the impulsive phase, it could measure neutrons produced during the impulsive phase, as the arrival time of neutrons near the Earth is expected to be 10-20 minutes later than that of the photons. By comparing the time profile of 19:58 UT (Fig. 2, left) with the spectrum of the second peak of 20:37UT (Figure 2, right), the latter seems to have a harder spectrum.

#### 4. Comparison of Observed Intensities between SNT and FERMI-LAT

Let us compare the counting rate observed by the FERMI-LAT detector with the counting rate observed by the SNT. The gamma-ray flux near the Earth measured by the FERMI-LAT around 20:15 UT is estimated as  $\sim$ 57 counts/m<sup>2</sup>/min. for  $E_\gamma > 100$  MeV.<sup>[11]</sup> In contrast, the gamma-ray flux of  $E_\gamma > 30$  MeV estimated from the counting rate measured using the SNT is 150,000 counts/m<sup>2</sup>/min. The flux of gamma rays estimated from SNT observation is about 2,500 times higher than that estimated from FERMI-LAT observation. One reason arises from the difference of the energy threshold ( $E_\gamma > 100$  MeV and  $> 30$  MeV). Another reason for this difference may stem from a situation where the FERMI-LAT detector did not observe the impulsive peak. In the flare on June 11, 1991, Rank et al.<sup>[16]</sup> and Kanbach et al.<sup>[17]</sup> reported that the intensity of gamma rays at the impulsive phase was about  $\sim$ 1,000 times more intensive than that of the gradual phase. Conversely, the SNT located on a high mountain may observe gamma rays emitted during the impulsive phase. However, the SNT could not observe an enhancement of gamma rays emitted during the gradual phase due to the high background.

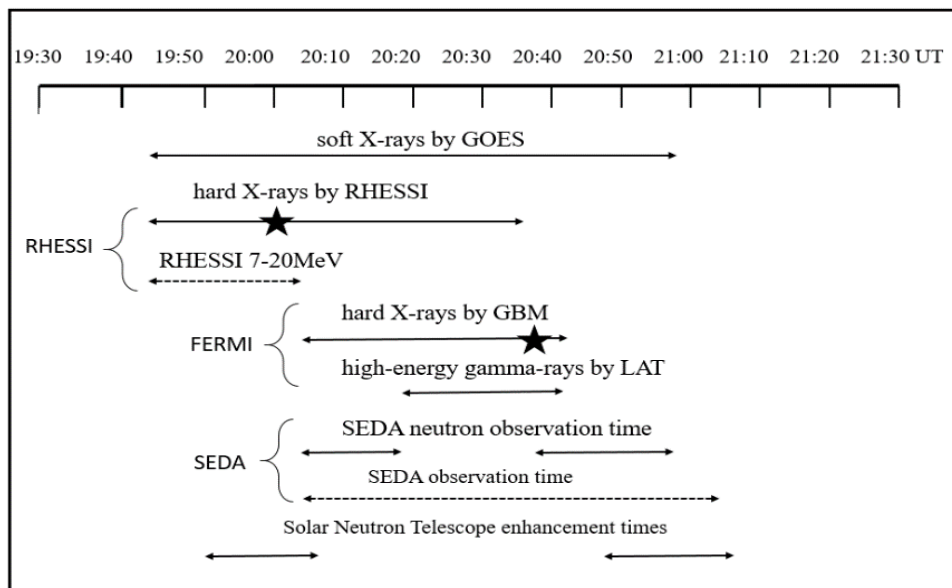


Figure 1. The event time profile of each detector as a function of universal time at 19:30–21:30 UT on March 7, 2011. The star mark ★ denotes the peak time of hard X-rays.

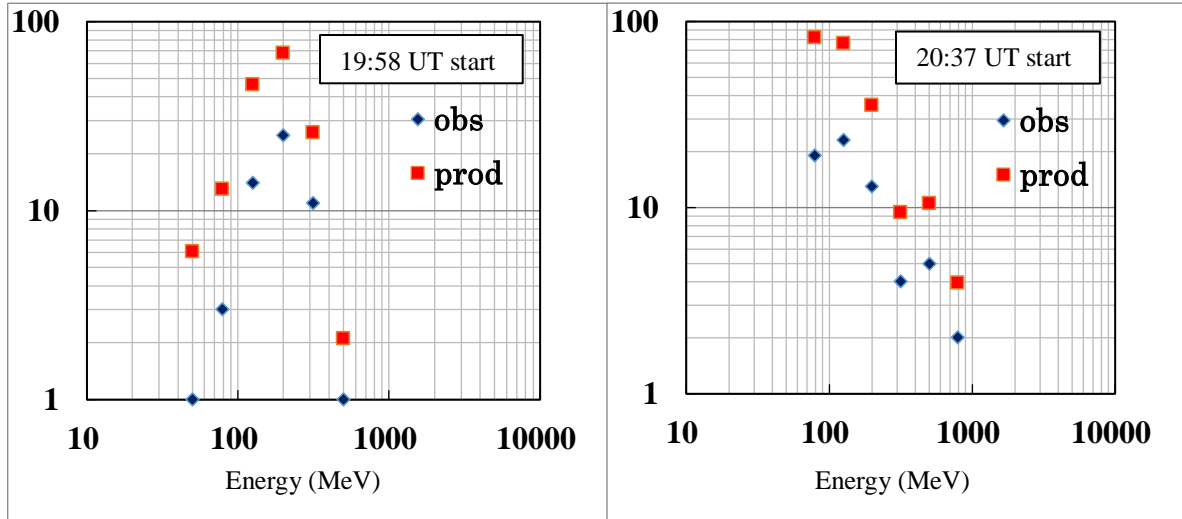


Figure 2. Energy spectra of solar neutrons for the 1<sup>st</sup> bump and 2<sup>nd</sup> bump. Here we assume that neutrons were produced instantaneously at 19:58 UT and 20:37 UT when soft gamma rays of 100-300 keV showed maximum intensity. From the flight time, the energy of solar neutrons is measured.

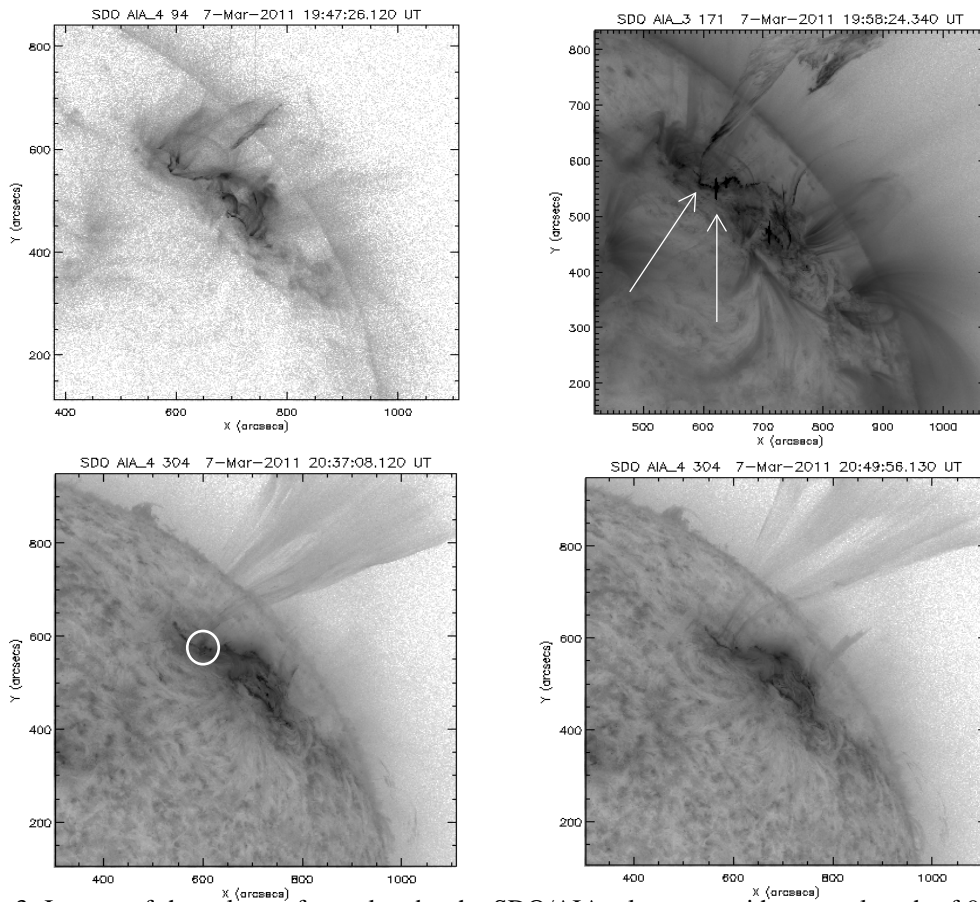


Figure 3. Images of the solar surface taken by the SDO/AIA telescopes with a wavelength of 9.4 nm at 19:47 UT (top-left), 17.1 nm at 19:58:24 UT (top-right), 30.4 nm at 20:37:08 UT (bottom-left), and 13.1 nm at 20:49:56 UT (bottom-right). At 19:58:24 UT, a flash can be recognized at 625'' and 555'' (the right arrow). Those hot particles may be transferred into the foot point of the CME at 595'' and 560'' (indicated by the left arrow), and then become seed particles for high-energy accelerated protons possibly located inside the shock of the CME (cannot observe it). Chen et al. estimated the start time of the CME at 19:43 UT. [11]

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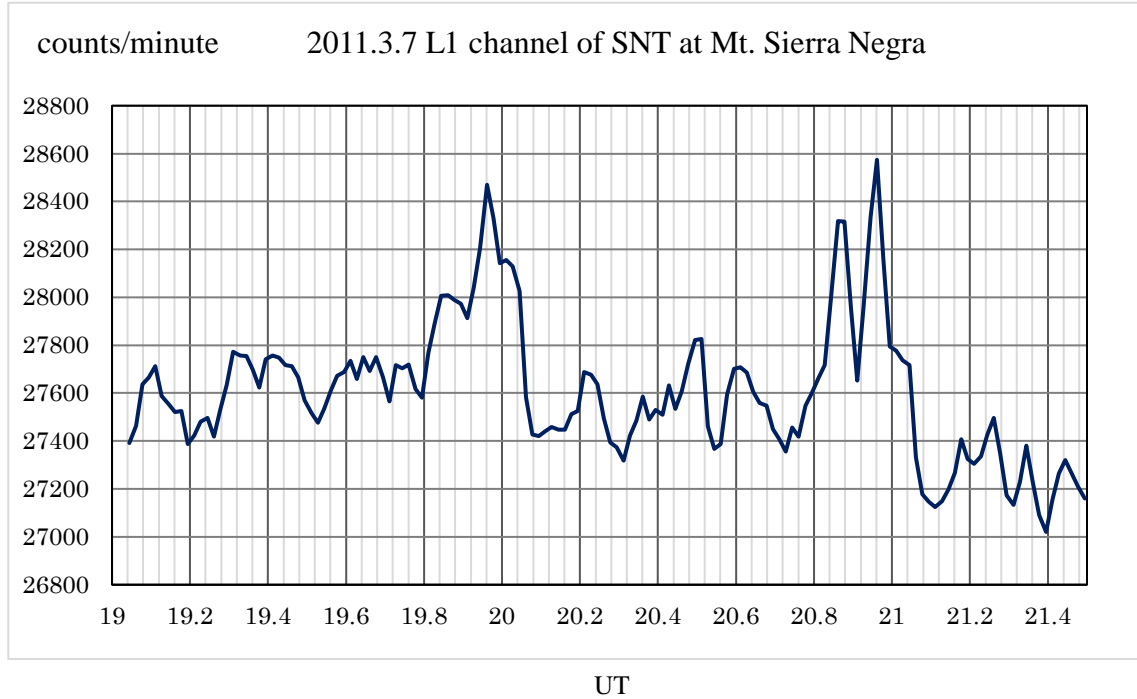


Figure 4. Three-minute running average of one-minute values of the L1 channel observed by the SN-SNT. The counting rate from 19:05 to 21:30 UT is shown. Two enhancements of the counting rate are recognized at 19h49m–20h02m UT (or 19.82–20.03 UT) and 20h50m–21h01m UT. The statistical significance is very high at  $9.7\sigma$  for the 1<sup>st</sup> peak and  $8.5\sigma$  for the 2<sup>nd</sup> peak. As an average background rate, we use 27,500 counts per minute.

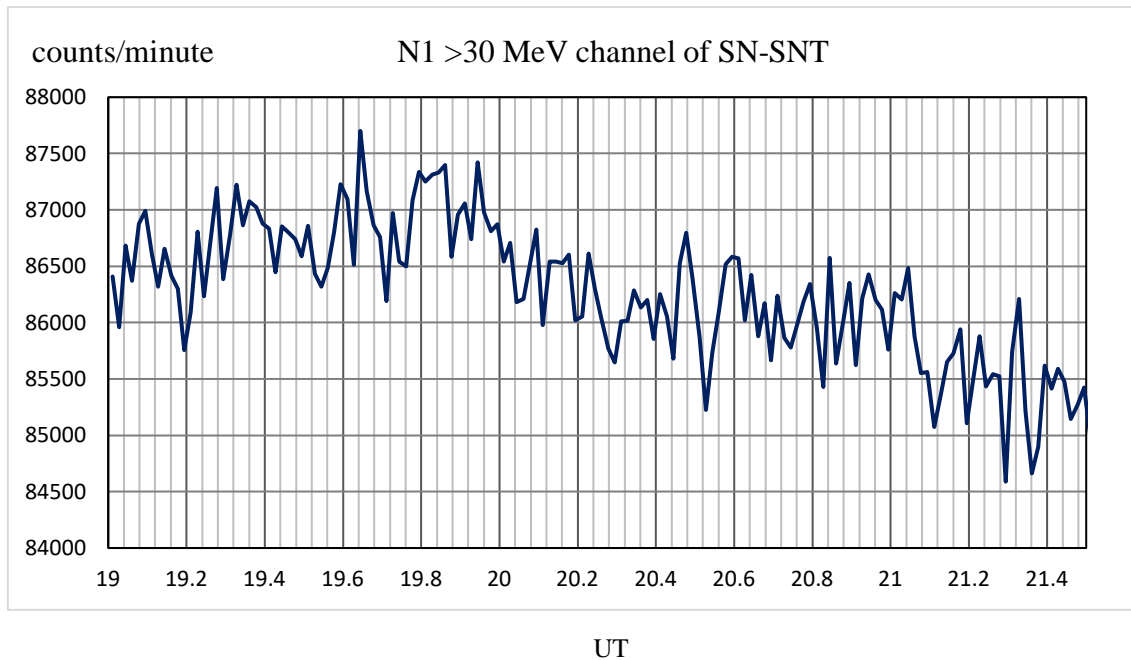


Figure 5. The counting rate of neutron channel N1. The vertical counting rate corresponds to the one-minute value for the 4-m<sup>2</sup> area scintillator. The N1 channel records neutral incident particles with energy higher than 30 MeV. The energy of the detector has been calibrated by using the energy deposited by passing muons. As seen in the above figure, no remarkable enhancements are recognized around 19.95 UT and 20.9 UT.

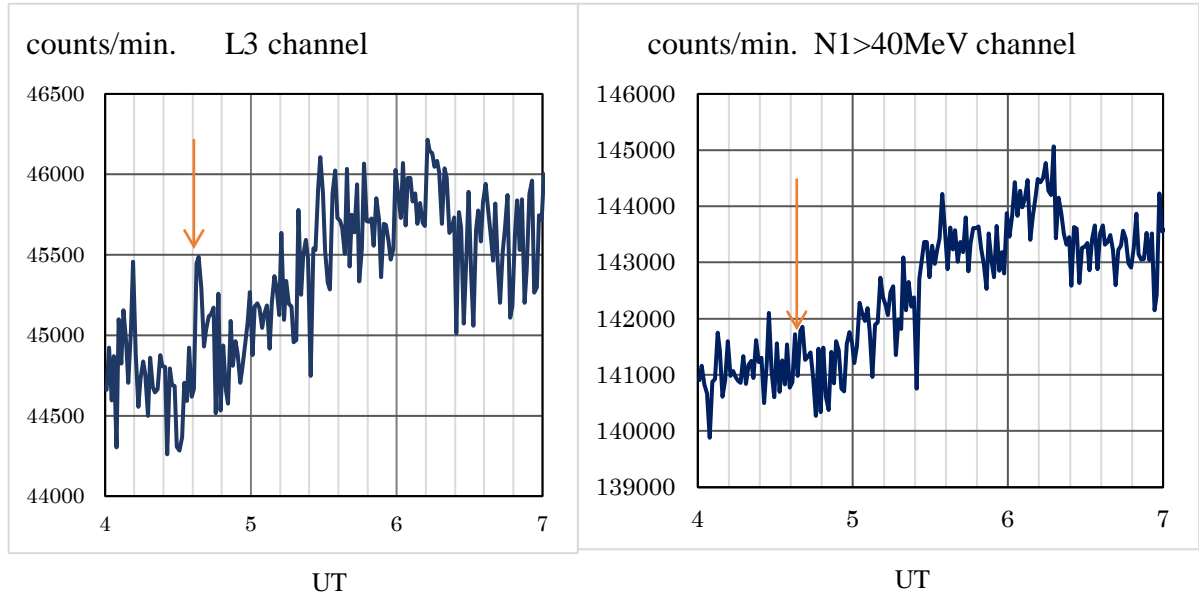


Figure 6. The enhancement observed by the SNT located in Tibet (4,300 m). The SNT has an area of 9 m<sup>2</sup> and the thickness of the plastic scintillator is 40-cm. **(left)** The counting rate of L3 channel. The enhancement started at 04:37 UT (12:37 Beijing Time indicated by an arrow). **(right)** The counting rate of neutron channel N1. No enhancement was observed by the neutron channel and also by the neutron monitor located at the same site. Therefore, we think that the enhancement was produced by gamma rays.

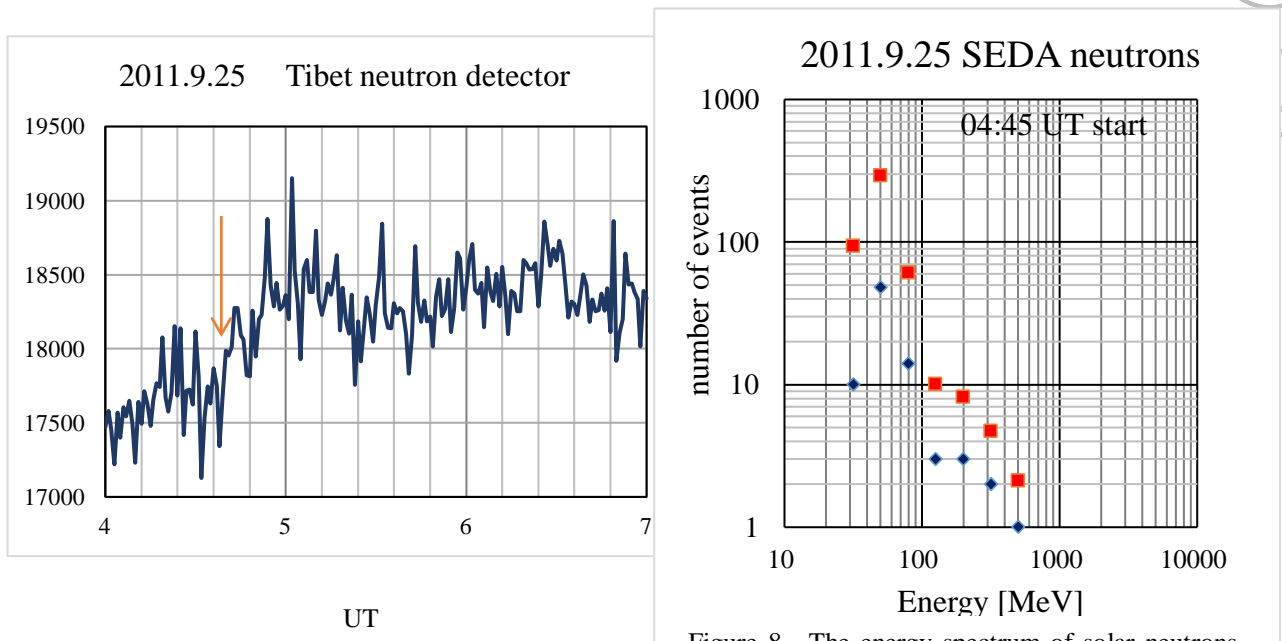


Figure 7. One minute value of the neutron-muon monitor located at the same site in Tibet (4300 m) <sup>[18]</sup>. No remarkable enhancement can be seen around 04:37 UT (indicated by an arrow). The data are corrected for the pressure effect.

Figure 8. The energy spectrum of solar neutrons estimated from the SEDA-FIB data, assuming instantaneous production of neutrons at 04:45UT. The blue diamond represents raw data, while the red box presents the corrected data of the decay effect.

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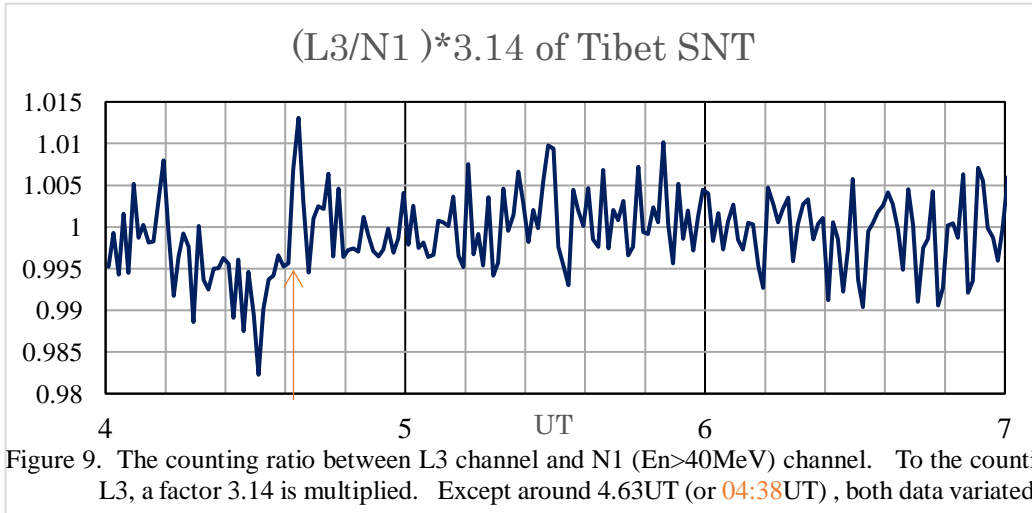


Figure 9. The counting ratio between L3 channel and N1 ( $E_n > 40$  MeV) channel. To the counting rate of L3, a factor 3.14 is multiplied. Except around 4.63 UT (or 04:38 UT), both data varied similarly.

## Summary and Conclusion

We have reevaluated the time profiles of high energy photons and neutrons observed by several detectors in association with the M3.7 flare on March 11, 2011. The different intensities recorded by the SN-SNT and SEDA may be consistently explained as gamma rays by a new MC calculation. The excess observed on September 25th, 2011 by the Tibet SNT may be also explained by the detection of solar gamma rays. To the best of our knowledge, there was no report on the detection of solar gamma rays by a ground based detector. This report may be *the first report* on the detection of solar gamma rays. Many cosmic ray detectors are located at high mountains. Gamma rays are a useful tool to study particle acceleration processes at the Sun. Details are given in arXiv1706.09082 [astro-ph,HE].

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