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Solar Neutrons and Particle Acceleration at the Sun: What We Learnt from Solar Neutron Telescope

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Abstract. The Sun provides unique opportunities for studying particle acceleration mechanisms from Earth. Particles may be accelerated to high energies by the first-order Fermi acceleration, by second-order Fermi acceleration, or by DC acceleration. Differentiating between these possibilities is a fundamental problem of cosmic ray physics. In this talk, a brief summary of past solar neutron events that occurred on June 21st 1980, June 3rd 1982, May 24th 1990 and June 4th 1991 will be presented. A particularly informative event that was detected on April 15th 2001 (the Easter event) by a suite of instruments including the Yohkoh Soft X-ray Telescope (SXT) will also be discussed. In addition, relatively recent events that occurred in September 7th 2005 will be discussed. New results on proton spectra of GLE (Ground Level Enhancement) events on April 25, 2001 will also be presented. Our results imply that particles are frequently accelerated to over 50 GeV in solar flares by Fermi's first-order shock acceleration mechanism.

Introduction

A brief history of solar cosmic rays

Cosmic rays were found independently almost 100 years ago by three distinct scientists, Drs. Hess, Kolhoerster, and Gockel around 1911-1912 [1]. At this time, these particles with extraordinary penetrating power were called "Höhenstrahlung"(high altitude rays). Recently, I became interested in the originator of the term "cosmic rays". I found the person was Robert Millikan, a Nobel prize laureate. He introduced the term "Cosmic Ray" in 1925. In a paper submitted to the American Academy [2], Millikan stated "those penetrating rays were of cosmic origin", and "cosmic rays, if they existed, had two or three times the ionizing effect to be expected from them at sea level".

Millikan measured the intensity of cosmic rays at a lake (altitude 3,540m) near the highest peak in the US, Mt. Whitney (4,418m). Afterwards, he moved down to another lake that was free of potassium, and again measured the intensity of cosmic rays with the same detector. Through a chain of such experiments, he learned that the differences in intensity at different altitudes were caused by absorption in the overlying thickness of atmosphere at each altitude. He then concluded that the rays must come from outside the Earth, and be of 'cosmic' origin.

The first information on the origin of cosmic rays was obtained by Scott Forbush in 1942. Forbush and his colleagues found that the intensity of cosmic rays increased by about 15% during a large solar flare on February 28, 1942 [3]. He therefore deduced that cosmic rays were produced, at least in part, by the Sun. This is the reason why the "penetrating rays from the Sun" were then called solar cosmic rays (SCR). Nowadays, they are referred to as solar energetic particles (SEPs). Surprisingly, the origin of the majority of cosmic rays has remained uncertain even to this day. They could be produced by SNRs (supernova remnants) and/or possibly by AGNs (active galactic nuclei). Today, we are still studying these and other possible cosmic accelerators using very large arrays of air shower detectors, and also large arrays of Cherenkov telescopes

Research aims

Numerous models have been proposed to account for the acceleration of particles near the Sun's surface. In addition, several space-based and ground-based instruments are now providing observational information. The latter are located at various places on the globe. As a consequence, the research has entered into a new stage where we can discriminate between the various acceleration models. Some interesting questions are being posed – which model is best able to explain particle acceleration at the Sun – when does acceleration occur, and by what means – and how is acceleration to high energy achieved? The latter question, in particular, is one of the most pressing.

Advantages of neutral beams from the Sun

Observations of the energy spectra of charged particles emanating from the Sun are, of course, useful. Observations neutral particles, however, do offer advantages. Our group has compared the times when charged particles are accelerated in relation to X-ray and gamma-ray observations. Because of magnetic effects in interplanetary space, charged particles from the Sun usually arrive at the Earth about one to a few hours later than the X-rays or gamma-rays (they are $\approx$ 500 seconds). Our studies of neutral particles have included both neutrons and gamma-rays. Gamma-rays may be either decay products of neutral pions with energies about 70 MeV, line gamma-rays with energy 4.4 MeV from the excited carbon or 2.223 MeV by the formation of deuterium or Bremsstrahlung from accelerated electrons. On the other hand, specific information on ion acceleration processes, unclouded by other effects, can be obtained through the neutron channel, because neutrons are produced solely by ions impacting the solar surface.

Detection of Solar neutrons

Returning to history, Biermann et al first pointed out in 1952 that neutrons produced in solar flares could be detected on Earth [4]. However, the detection of solar neutrons was not made for some 30 years when they were discovered in the solar flare of June 21, 1980, by instruments aboard the SMM satellite [5]. The first detection of solar neutrons by ground level detectors was made in 1982 using neutron monitors located at European observatories during the solar flare of June 3 of that year [6]. In this flare, protons from neutron decay were also observed [7]. In the solar cycle 21, only two solar neutron events were observed. Therefore, it has been believed for a long time that the detection of solar neutrons is very difficult, comparable to other rare processes that are inherent to cosmic ray physics.

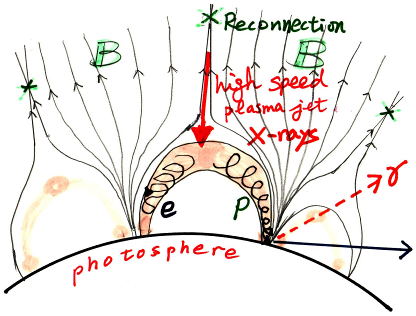


Fig. 1. Particle acceleration model at the solar surface. By collision and reconnection processes of magnetic loops, the plasma in the loop is warmed up. The warm plasma then forms a high speed plasma jet and the stream hits the top of the lower magnetic loop. Particles in the lower magnetic loop pass through "the plasma jet wall" by the mirroring process. As a consequence of 'back and forth processes', particles increase their energies with every pass by the parallel shock acceleration mechanism.

The production mechanism of solar neutrons

The production mechanism for solar neutrons that is favored by many solar physicists is the one depicted in Fig. 1 [8].

The collision of the magnetic loop is the origin of particle acceleration. At first the plasma within the magnetic field lines is warmed due to the reconnection process. The warmed plasma then blows down from the top to the bottom forming a plasma jet. The plasma jet stream hits the top of a magnetic loop. Particles within an inverse U-shape magnetic loop will be accelerated by the collision process with the plasma jet. Typically, the speed of the plasma jet is about 3,000 Km/s (or $v = 1/100$ c). When particles pass through the plasma jet wall, their energies are boosted by an amount ΔE where $\Delta E = 2v/c = 0.02$. If they pass through the wall some 385 times, the energy may be boosted from 20 MeV to 40 GeV ($1.02^{385} = 2,046$). If we assume the size of a magnetic loop is of order 10,000 Km, the time needed for acceleration is only about 70 seconds – quite brief. Of course, this estimation is very crude, and the actual acceleration process may be more complex. However, it is plausible that particle acceleration occurs by passing through the plasma jet wall back and forth repeatedly [9]. This scenario may be tested by observation. The main part of this talk will be directed towards demonstrating this, and will be based on "multi-wave-length" observations that have been made extensively with modern instruments.

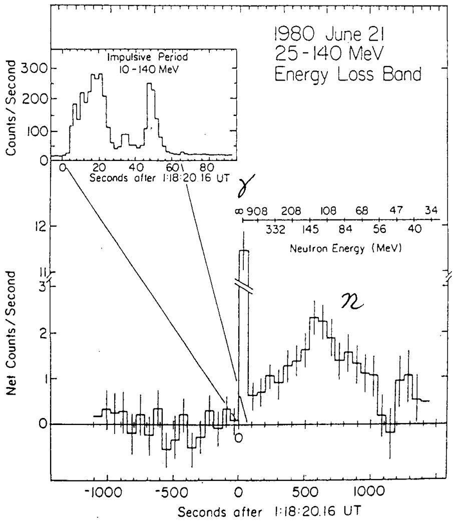


Fig. 2. The first solar neutron event discovered by the detectors onboard the SMM satellite. The first spike was produced by photons and the following broad bump by neutrons. The time profile of neutrons can be explained by a simple impulsive production model.

Basic properties of solar neutrons and historical neutron events

To present the argument smoothly, we first recall some basic properties of solar neutron physics. As neutrons have mass, they cannot run with the speed of the light. Neutrons with energy 1 GeV require one minute longer than photons to travel from the Sun to the Earth, and for neutrons of energy 100 MeV the time lag is 11 minutes. So even if they are emitted simultaneously at the Sun, their arrival times on Earth differ substantially, as in a marathon. Put another way, both the energies and arrival times of neutrons at Earth need to be measured in order to establish their emission times. This is the so-called "velocity dispersion" effect of neutrons. It renders the distinction between continuous and impulse production of solar neutrons quite complicated. It was for this reason, *viz.* to understand the dynamics of acceleration processes occurring at the Sun, that we developed solar neutron telescopes with the ability to measure both arrival times and arrival energies. Details of our telescopes, which utilize plastic scintillators, may be found elsewhere [10].

An illustrative example is shown in Fig. 2. This applies to an event observed on June 21, 1980 [5]. One can see that after the first sharp peak, a broad hump follows. The first peak must be produced by gamma-rays, whilst the second enhancement must be produced by neutrons. Even if the neutrons left the Sun almost at the same time (within one minute), their arrival times would be spread over a time span of 20 minutes, with high-energy neutrons arriving fast and low-energy neutrons arriving later. For the first 10 minutes, the flux was seen to increase, but after that it decreased. This is due to the decay effect of low-energy neutrons in transit. The differential energy spectrum ($dN/dE \propto E^{-\gamma}$) can be expressed by a power index $\gamma = 3.5$ assuming impulsive production at the Sun. The spectrum for this event was relatively hard. Also, from the observational point of view, the possibility remains that neutrons with high energies (say $\gtrsim$ 1 GeV) were continuously produced for more than 17 minutes.

For the next event, an event observed on June 3, 1982, the situation was more complex. Fig. 3 shows the data [6]. The ground level neutron monitor showed an enhancement that continued for more than 14 minutes. According to a recent Monte Carlo simulation [11], neutrons with energy less than 70 MeV cannot reach the ground due to strong attenuation in the atmosphere, because the interaction cross-section of neutrons with the air increases rapidly below 100 MeV.

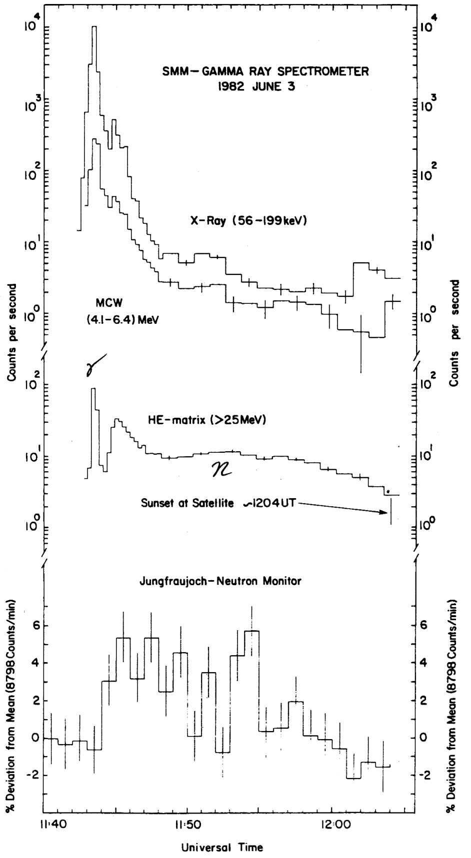


Fig. 3. The first neutron event detected by a ground level neutron monitor. The first spike was caused by photons, and the following hump by neutrons (the middle data). This continued for more than 20 minutes. The data of the ground level neutron monitor (bottom) shows a clear enhancement that continued for 14 minutes at least.

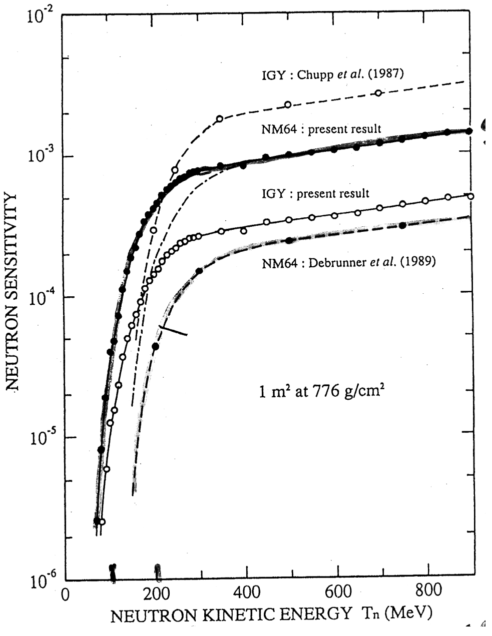


Fig. 4. Sensitivity curve of solar neutrons in the atmosphere. Sensitivity decreases below 100 MeV because the total interaction cross-section with atmospheric nuclei increases. The "NM64:present result" corresponds to the result calculated by Shibata [11] being based on a different interaction model for the neutron monitor type NM64.

Fig. 4 displays the sensitivity curve of neutrons in the atmosphere [11]. For energies greater than 200 MeV, the sensitivity depends only weakly on energy. The sensitivity is approximately 1/1000. Thus for every 1000 neutrons arriving at the top of the Earth's atmosphere, only one survives to mountain altitude ($\sim$ 776 g/cm^2).

Neutrons with energy 70 MeV are delayed by 14 minutes with respect to light. However the data of June 3, 1980, shows the arrival of neutrons for a time span in excess of 14 minutes, indeed by a further 6 minutes (according to the data shown in the middle panel of Fig. 3). If this tendency could be applied to the time profile of the neutron monitor, it follows that, in this event at least, some gradual production of neutrons might have occurred. However the signal after 11:58UT was weak and the background level.

Fig. 5 shows another event observed on May 24, 1990. A huge bump produced by neutrons is seen. Following this bump which was induced by a "neutron GLE", a "traditional GLE" produced by protons can be recognized. The energy spectrum of solar neutrons can be expressed by the power law with the differential index $\gamma = 2.9$ [12].

Fig. 6 presents data of an event on June 4, 1991, that was detected at the Mt. Norikura cosmic ray observatory by three different kinds of detector simultaneously, a traditional neutron monitor, a new 1 m^2 neutron telescope, and a 36 m^2 muon detector [13]. The power indices for them are given in Table 1. Watanabe included the above events in a summary of neutron events (Table I) that were

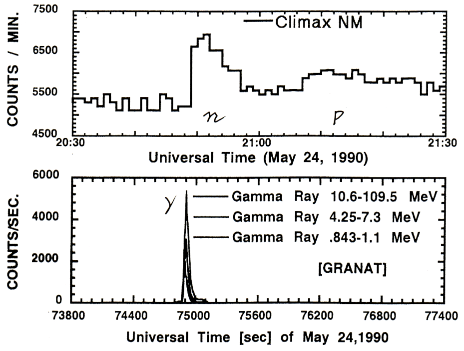


Fig. 5. Solar neutron event observed on May 24, 1990. This event is well known as the first event in which solar neutrons induced a GLE. The production spectrum of neutrons can be fit by the power law with the differential power index $\gamma = 2.9$ and are consistent with an impulsive production model.

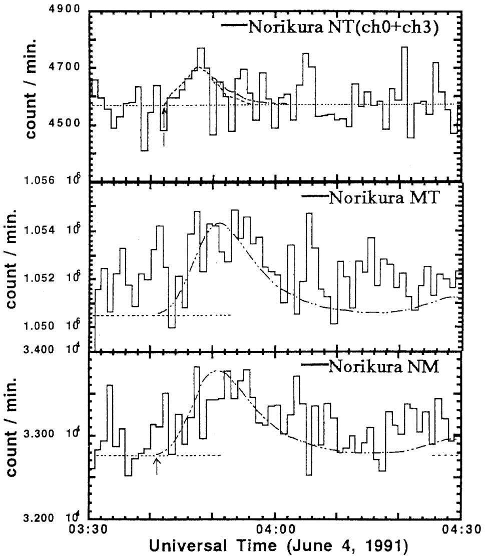


Fig. 6. Solar neutron event observed in July 4, 1991. This was the first solar neutron event to be observed by a neutron telescope. Three detectors located at the Mt. Norikura observatory observed the enhancement induced by solar neutrons simultaneously. The figure shows an enhancement ob-served by the 1 m^2 neutron telescope (top) and the 36 m^2 muon detector (middle). The time profile recorded by the neutron monitor (bottom) was almost the same as that recorded by the 36 m^2 muon detector.

detected by the neutron monitors [14]. It would be of interest to see if all solar neutron events can be described by power laws with (differential) power indices γ between 3 and 4. This would suggest that the parent protons also follow a power law, as anticipated by shock acceleration theory.

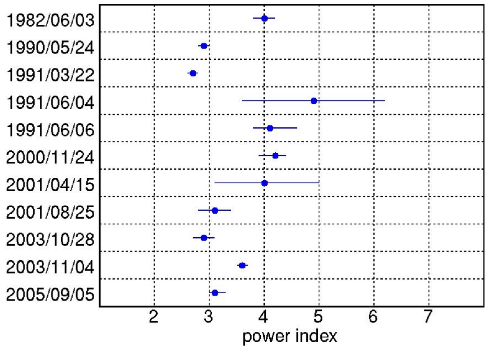


Table 1. The power index of solar neutron events detected by the neutron monitors with energy range around E_n=70-700MeV. The events detected only by solar neutron telescopes have been not involved in.

Characteristics of solar neutron detectors

Consider first the traditional neutron monitor. This detects both neutrons and protons. These interact with a lead target in the detector producing further neutrons. The neutrons undergo successive collisions with protons in paraffin surrounding a BF_3 gas counter, and thereby lose momentum and are gradually thermalized. The thermal neutrons enter into the BF_3 gas counter located in the centre of the neutron monitor, where they are trapped by boron gas. Alpha rays are then produced in the process: $^{10}\mathrm{B} + \mathrm{n} \rightarrow \alpha + ^7\mathrm{Li}$. In this way, neutrons are detected *via* signals of α-particles. The discrimination level of the BF_3 counter is set at a charge level Ze $\gtrsim$ 2, so that the detector is free of an enormous background consisting mainly of minimum ionizing muons and electrons. However, as the incoming neutrons are thermalized, all knowledge of their original energies is lost.

As described above, knowledge of the energies of incident neutrons detected at Earth is essential for discriminating between various possible acceleration mechanisms occurring at the Sun. This was our motivation for installing a worldwide network of energy-measuring solar neutron telescopes (SONTEL) on high mountains. The principle of the neutron telescope is based on a charge exchange process between neutrons and protons. Incoming neutrons enter into a plastic scintillator where they collide with protons. In this process, neutrons are effectively converted into protons. The momentum of the incoming neutron is transferred to protons. When a neutrons hits a hydrogen target, the energy of neutrons is uniquely determined by the kinematical relationship:

$$E_n = E_p \sin\theta^2.$$

Here θ is the emission angle between the outgoing protons with respect to the incoming neutron. The energy of a neutron can be measured from the track length of protons. However, when neutrons collide with carbon nuclei in the plastic scintillator, only a minimum energy of the incoming neutron is recorded. This is because multiple emissions of not only protons but also neutrons occurs in this case.

In the following section, data for a beautiful event that was observed on September 7, 2005 are displayed. The data were obtained by a neutron telescope at Sierra Negra mountain, and by a neutron monitor at Chacaltaya observatory. This example illustrates the capabilities of these types of detectors.

September 7, 2005 neutron event observed at Sierra Negra and Chacaltaya

The solar neutron telescope mounted at Sierra Negra is shown in Fig. 7. Similar solar neutron telescopes have also been located at Gornergrat (Switzerland) [15], Tibet (China) [16], Mt. Norikura (Japan) [17], and Mauna Kea (Hawaii, USA) [18]. Mexican astronomers at INAOE (The Instituto Nacional de Astrofisica, Optica y Electronica) are presently installing the large millimeter radio-telescope atop the Sierra Negra mountain (4600 m a.s.l., 19.0N 97.3W) shown in Fig. 8. They have installed a power line from a village at the foot of the mountain. We have negotiated a proposal with INAOE to use their power supply for the operation of a cosmic ray detector at the same site. The academic staffs of INAOE have kindly accepted this proposal, and construction of a solar neutron telescope at the site has commenced. This is shown in Fig.9, together with Mexican cosmic ray scientists, technicians of UNAM and Japanese cosmic ray physicists.

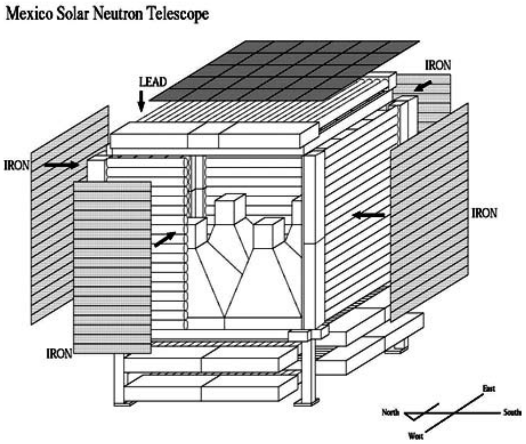


Fig. 7. Solar neutron telescope located at Mt. Sierra Negra (4600 m) in Mexico. Solar neutrons are converted to protons by the plastic scintillator. The plastic scintillator is surrounded by the anti-counters consisting of proportional counters. The arrival directions of solar neutrons are measured by converted protons in 4 layers of proportional counters located underneath of the plastic scintillator.

Fig. 8. Location of Sierra Negra observatory in Mexico. The latitude and longitude is at 19.0N and 97.3W respectively. The INAOE collaboration have constructed a large millimeter radio telescope there (at LMT).

Fig. 7 shows the detail of solar neutron telescope at Sierra Negra [19]. It consists of 30 cm thick plastic scintillator with an area of 4 m^2.

This is used for the measurement of the energies of neutrons as described above. The arrays of

Fig. 9. Solar neutron telescope under construction at Sierra Negra on March 12, 2003.

the proportional counters beneath the plastic scintillator are used for the measurement of directions of incoming neutrons, as is also described above. Surrounding these detectors, an anti-gondola is prepared for the identification of not only charged particles but also neutral particles.

The detection efficiency of neutrons is about 30% and the arrival directions of neutrons are determined to an accuracy of about ±15. Iron plates of thickness 2cm are located on the four sides of the anti-counter to convert gamma-rays to charged particles whilst passing neutrons. At the top of the anti-counter a 5mm thick lead plate is installed for a similar purpose. However the efficiency of the anti-counter is $< 100\%$. It is estimated to be $\sim 80\%$ due to lack of the coverage (gap), and also the conversion rate of photons to charged particles in the lead and iron plates. Thicker plates might be better at the expense of converting a fraction of incoming neutrons to charged particles and hence being effectively lost.

The detector records energy deposits by neutrons in 4 ranges, $>$30, $>$60, $>$90 and $>$120 MeV. This sets the limit for testing production solar models of neutrons. Since neutrons with an energy of 120 MeV trail light by 9 minutes, an excess of neutrons recorded in the channel $>$120 MeV beyond 9 minutes signifies continuous acceleration of protons and production of neutrons at the solar surface. The reverse indicates instantaneous production and acceleration of protons within about one minute at the Sun.

The September 7, 2005 event is one of the high-light events of this conference [20]. So I will explain it in a little detail here. The flare occurred at position S06E89 on the Sun. At the time, the Sun was above the Atlantic side of the American continent. The intensity of solar neutrons was extraordinarily strong, and four detectors located at Sierra Negra and Chacaltaya made successful detections. This provided an opportunity to compare the detection efficiency of the solar neutron monitor at Chacaltaya and the neutron telescope at Sierra Negra.

Fig. 10 displays the respective responses for this flare. The neutron monitor at the Chacaltaya observatory recorded 95,000 neutrons during 10 minutes, while the neutron telescope at Sierra Negara recorded 21,500 events for $E_n > 30$ MeV, 11,700 events for $E_n >$ 60MeV, 3,000 events for $E_n >$ 90MeV and 820 events for $E_n > 120$ MeV.

They are 22.6, 12.3, 3.2 and 0.8% of the numbers detected by the neutron monitor, reflecting the energy spectrum of the arriving neutrons. The detail of the Chacaltaya neutron counter can be seen in elsewhere [21]. The detection efficiency of the Sierra Negra neutron telescope for solar neutrons per unit area is estimated to be nearly equal to that of neutron monitor ($\sim$ 30%) [22].

The area of the Chacaltaya neutron monitor (12 m^2) is three times larger than that of the Sierra Negra neutron telescope (4 m^2). Taking into account

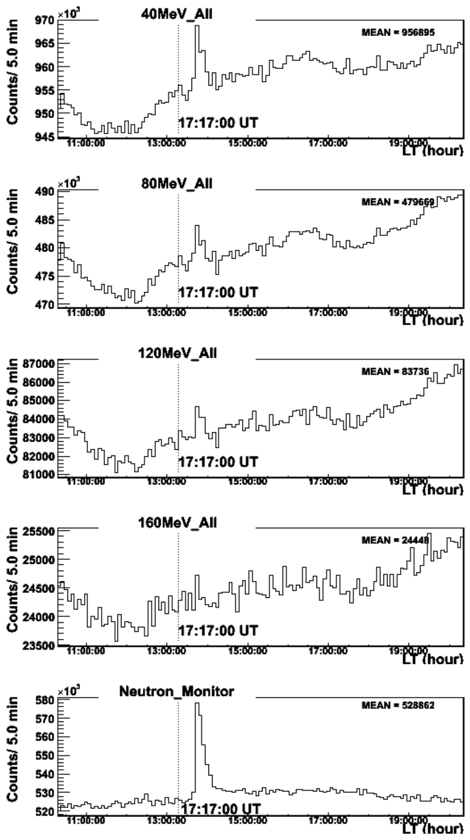


Fig. 10a. Five minute values observed by the solar neutron telescope and the neutron monitor at Chacaltaya for the September 7, 2005 event.

the difference in the acceptance of the two detectors, the counting rate of the neutron telescope at Sierra Negra was 22.6× 3% of the Chacaltaya neutron monitor.

In other words, the counting rate per unit area of the neutron telescope was 67.8 % that of the neutron monitor. However, the neutron monitor usually provides an over count. If we allow for this effect, the detection efficiencies of the two detectors per unit area are seen to be nearly the same. The difference of atmospheric depths between Chacaltaya and Sierra Negra for this event was only 29 g/cm^2, and was not allowed for in the present analysis. The actual depths, including the zenith angle effect, were 558 g/cm^2 at Chacaltaya and 587 g/cm^2 at Sierra Negra. These values were included the short path effect by the large-angle scattering of neutrons which occurs in the atmosphere [23].

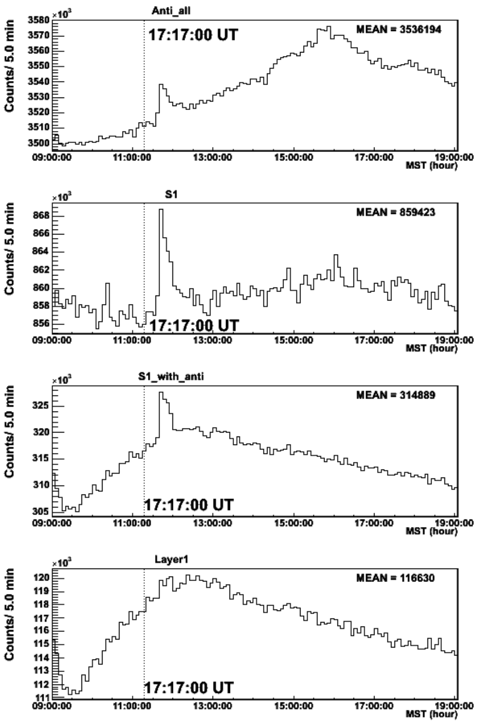


Fig. 10b. Five 5 minute values observed by the solar neutron telescope and the neutron monitor at Sierra Negra on September 7, 2005 event.

Here a note is made for Fig. 10b S1 corresponds to the channel $E_p > 30$MeV, S1_with_anti for $E_n > 30$MeV, anti_all for the counting rate of total anti PR counters and Layer 1 for the counting rate of the layer underneath of the scintillator. Ep includes all charged particles not only protons but also electrons and muons. The different time profiles between Anti_all and Layer 1 detectors arise from the energy difference of the response against the pressure and the temperature. The 40 MeV all of Fig. 10 represents the counting rate of all charged particles.

An attempt was made to interpret the data with a (temporal) delta function production model. Such a model successfully accounted for the flare on May 24, 1990. However, in the case of the flare of September 7, 2005, although the major part of the production could be explained with a simple power index γ = 3.1 $\pm$ 0.1, tails to the distribution were found that deviated from the delta function model. This might indicate continuous acceleration of protons at the Sun, or induced by the dropped-off protons to the solar surface that were trapped in the magnetic loop. Unfortunately, the RHESSI satellite was in the South Atlantic Anomaly during this event, thus preventing further information being obtained on the acceleration of particles in the magnetic loop.

Highlights of April 15, 2001 event

Solar activity was very high from the end of March 2001 to the middle of April 2001. Many gigantic flares (including 9 X-class flares) were observed and some interesting events were accumulated [24]. Among them I would like introduce one observed event on April 15, the Easter day of 2001. Since it was observed on Easter day, it is sometimes referred to as "the Easter event". The development of magnetic loops was clearly observed by the Yohkoh Soft X-ray Telescope (SXT) during this event.

The start of the flare was detected by the GOES satellite at 13:19UT. The flare grew with time and the intensity of X-ray emission reached level C4 at 13:23UT. X-ray emission then strengthened greatly and reached level M1 at 13:40UT. At 13:43 UT, it exceeded X-class for a short time, and at 13:50UT, it peaked at X14. (The logarithmic A, B, C, M, X intensity scale for solar X-ray emission is used here.) The above flare of X14 class was one of the strongest flares observed during the solar cycle 23.

The Yohkoh satellite recorded line gamma-rays between 13:45UT and 13:51UT, implying that protons were accelerated impulsively to high energies between 13:43 UT and 13:47 UT. High energy protons and helium nuclei evidently impacted with helium or carbon nuclei in the solar atmosphere and produce the line gamma-rays.

The detection of the line gamma-rays provides evidence for proton acceleration at the Sun.

We have investigated the data observed by the ground level detectors carefully. The neutron monitor at the Chacaltaya observatory (altitude 5,250m) recorded a bump after 13:51 UT that continued until 14:15UT. The significance of the bump was $5.2\sim$ 6.4 σ. However fluctuation of the counting rate observed by the neutron monitor does not follow a Gaussian distribution. Instead, the deviation of the count rate divided by 1.52 does, where the factor 1.52 arises from multiple neutron production in the lead target of the neutron monitor. Then it turns out $3.4\sim$ 4.2 σ [25]. As shown in Fig.11, in the 3 minute time profile of the counting rate, a second peak was detected. As this coincided with the arrival time of the GLE, we assume it was produced by GLE protons. The rigidity cut-off of the Chacaltaya observatory is 12.1 GV [26], so low-energy protons cannot reach the observatory. However, high-energy protons can penetrate over Chacaltaya.

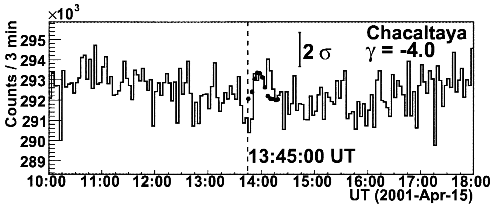


Fig. 11. Three minute values of the Chacaltaya neutron monitor on April 15, 2001. The line at 13:45:00 UT is the estimated time of particle acceleration and the red dots represent the expected curve for the impulsive production of neutrons with γ= 4.0. Around 14:06-14:12UT, there is another enhancement due to the GLE, caused by high energy protons.

The local time at Chacaltaya was 10 am. There-fore the observatory looked the direction of the interplanetary magnetic field line ($\sim$9am). Since the position of the flare was near the west limb of the Sun (S20W85), the sky of the Pacific coast of American continent and the position of the flare at the Sun (the west limb) is well connected by the interplanetary magnetic field. Therefore high energy charged particles emitted into the interplanetary space can easily arrive at Earth, being transported in the magnetic field line. Remember the rotation radius of the particles with momentum 10 GeV/c is $\sim$ 0.1AU (by the equation p =300Hρ and for H$\approx$ 20 μ gauβ). So particles with momentum less than 10 GeV/c are certainly trapped in the magnetic field and transported into Earth. Therefore in many stations located at American continent, Europe and Antarctica the GLE induced by the particles (with momentum less than 10 GeV/c and higher than each rigidity) was observed in association with this flare [27].

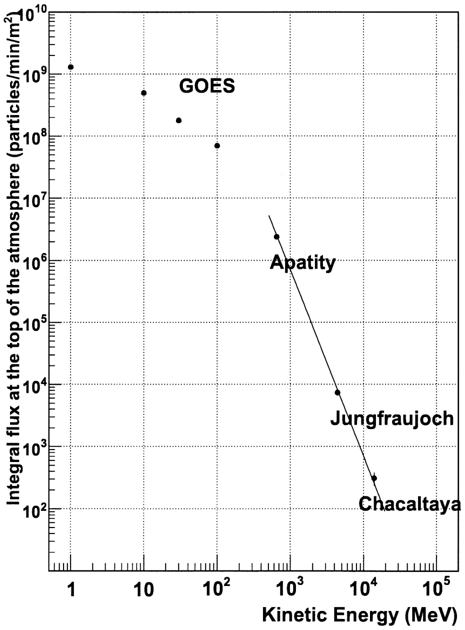


Fig. 12. Integral proton spectrum of the solar cosmic rays observed on April 15, 2001. The four data points at low energies were supplied by the GOES satellite. The other points were obtained by the ground based detectors. The plot includes data taken at Apatity (rigidity 400MV), Jungfraujoch-Gornergrat (4.44GV) and Chacaltaya (12.1GV). The data from the ground-based detectors can be expressed by a power law with power index γ = 2.75 $\pm$0.15. The data point of Notre Dame muon shower detector fits an extrapolation of these data. The average energy of primary protons corresponds to 56 GeV.

Fig. 12 shows the proton flux. The figure was constructed as follows. The peak flux at each station was assumed to correspond to the local rigidity, irrespective of time differences between the peaks, and combined using a logarithmic scale. The data points from Apatity (Russia), Jung-fraujoch-Gornergrat (Switzerland) and Chacaltaya (Bolivia) were found to fall on a straight line, corresponding to an arrival flux of protons at Earth with an integral power index γ= 2.75$\pm$0.15 in the energy range 0.4 to 12.1 GeV.

At the conference at Merida, I had the chance to converse with Prof. Poirier of Notre Dame University (Indiana, USA) where a muon detector (GRAND) is located. An enhancement was recorded by this detector from 14:00UT to 14:30UT on April 15, 2001 [28]. The excess was 12 ± 3 min^{-1} m^{-2}. The mean incident energy of primary cosmic rays for the GRAND detector is estimated to be 56 GeV. If we add this datum to Fig. 12, we see, perhaps surprisingly, that it aligns with an extrapolation of the above straight line! This suggests that protons were accelerated to energies exceeding 50 GeV in this flare, and possibly in excess of 100 GeV. The threshold energy was estimated by us as to be 30 GeV [29].

To my knowledge, this is the first clear evidence for the arrival of such high energy particles from the Sun [30]. It was confirmed using multiple detectors. It also resolves the long-standing question of whether solar cosmic rays are transferred directly without being trapped by the interplanetary magnetic field, or trapped [31]. The observations indicate that solar cosmic rays with energies as high as 56 GeV are trapped by the interplanetary magnetic field and transported to the Earth. (Remind a fact again that a typical rotation radius for protons with momentum of 10 GeV/c is about 0.1 AU.) In the present event we may conclude that the above excess observed at Chacaltaya between 13:51UT and 14:01UT was induced by solar neutrons.

To close this section, I should like to present beautiful data taken by the SXT onboard the Yohkoh satellite in association with this flare. As shown in Fig. 13, one can see the acceleration site of particles by the X-ray telescope! The Yohkoh images show that the plasma involved in the two loops were warmed by the reconnection process induced by the collision of the two loops at 13:32UT-13:47UT. The warmed plasma was then transported into another loop forming a plasma jet (13:39UT). The plasma jet impacted the top of another loop located at lower altitude. Particles in the lower loop must have repeated a backward-forward motion inside the loop by the mirroring process and penetrated through the plasma jet wall (13:47:12UT). By the parallel shock acceleration process, particles were repeatedly accelerated into high energies [32]. The images shown in Fig. 13 reflect the above scenario.

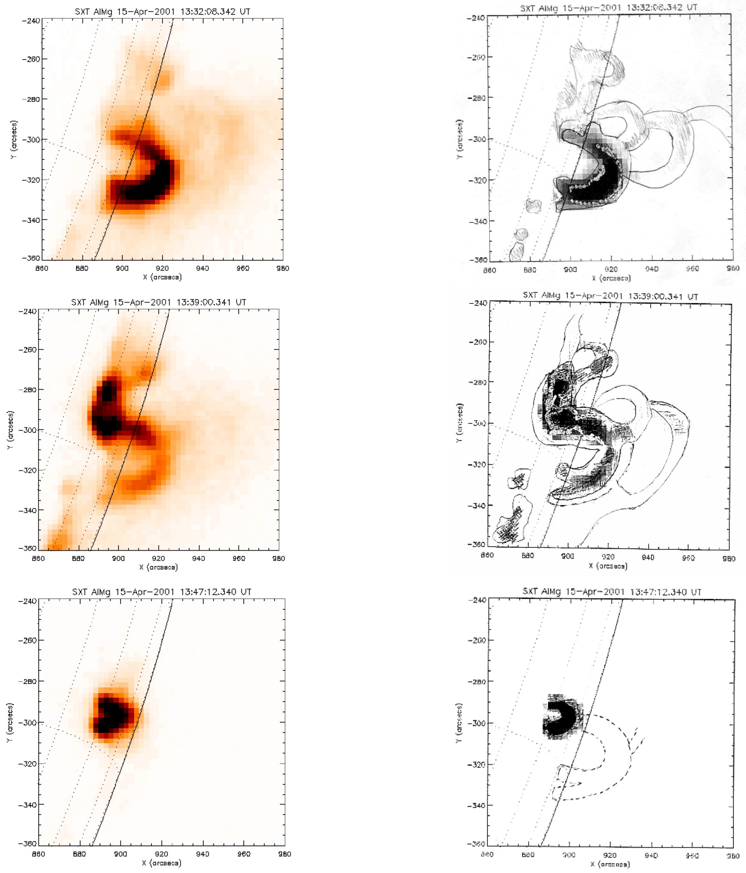
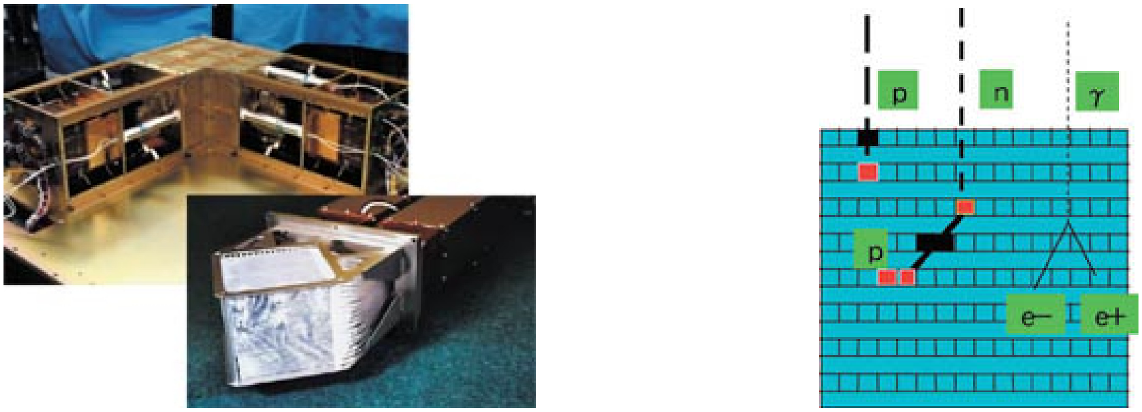
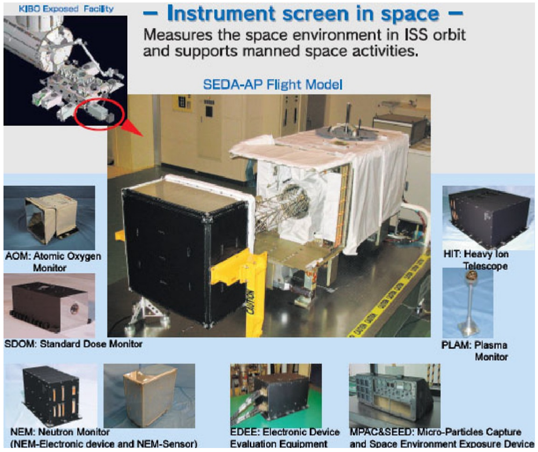


Fig. 13. The Yohkoh images of the flare taken by the SXT. The first two slides were taken at 13:32UT-13:37UT (C4 level) and the second two panels were taken at 13:39:00UT(M1 level). The third two slides were taken at 13:47:00UT when the X-ray emission increased from X6 to X14 level. At this time, particles involved in this loop may be accelerated into high energies.





– Instrument screen in space –

Measures the space environment in ISS orbit and supports manned space activities.

Fig. 14. A fiber detector for solar neutrons (top left side graph) in SEDA (bottom graph). Scintillation Fiber Detector (FIB) is assembled by mutually-perpendicular scintillation sticks (16×16). It measures tracks of recoil proton from each lot by multi anode photomultiplier and estimates energy and incident direction of neutron by its amount of light emission and tracks. Discriminating neutron from proton can be achieved by taking anti-coincidence with light emission from scintillator at outermost layer. (charged particles will emit light at outermost scintillator) Discriminating neutron from photon can be achieved by the difference of tracks. (neutron: 1 track, photon: 2 tracks) (top right side graph)

Future tasks

I would like to describe interesting tasks that are planned for the forthcoming solar cycle 24.

1. The search for the highest energy solar cosmic rays will be an exciting subject. Does the Sun accelerate particles to 1 TeV? The above observation by the Notre Dame detector indicates that small muon detectors located at shallow depths underground, together with small air- shower detectors located at mountain altitudes, could resolve this question.

2. Simultaneous observation between SXTs onboard the Hinode satellite and ground level neutron detectors will be promising. The single event observed on April 15, 2001 does not suffice to understand the dynamics of particle acceleration at the Sun. With the accumulation of more data, we could discriminate between various acceleration models for particles at the Sun.

3. The rejection power for charged particles by the anti-counter of present solar neutron telescopes is insufficient. There is a space (about 20%) that is not covered by the anti-counter, and charged particles are penetrating through these gaps as if they were neutral particles. The improvement of the particle identification ability of present solar neutron telescopes is an important task. The huge background presented by muons and electrons can then be controlled. This will enable good quality data to be obtained with high S/N ratio using solar neutron telescopes. We recorded over 30 solar neutron candidate events during solar cycle 23 with neutron telescopes [33]. However, their statistical significances are at the 3σ level. By doubling the S/N ratio of the telescopes, these candidates will be confirmed with a statistical significance of 4.5σ.

4. Simultaneous observations between the ground-based solar neutron detectors and the neutron detector at SEDA will be promising. The SEDA detector will be launched by the space shuttle Atlantis in April 2009 (Fig. 14). The neutron detector onboard SEDA will record energies of neutrons from 30 to 100 MeV [34]. This detector should be able to answer the long-standing puzzle on pure impulsive versus impulsive plus gradual complex emission of neutrons at the Sun.

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