Status of the world-wide network of solar neutron telescopes in solar cycle 24

Y. Matsubara*, Y. Muraki*†, T. Sako*, Y. Itow*, T. Sakai‡, S. Shibata§, T. Yuda¶, M. Ohnishi¶, H. Tsuchiya$^{\|}$, Y. Katayose**, K. Namikawa††, R. Ogasawara‡‡, Y. Mizumoto‡‡, F. Kakimoto^{x}, Y. Tsunesada^{x}, K. Watanabe^{xi}, E. Flückiger^{xii}, R. Bütikofer^{xii}, A Chilingarian^{xiii}, G. Hovsepyan^{xiii}, Y. Tan^{xiv}, J. L. Zhang^{xiv}, R. Ticona^{xv}, W. Tavera^{xv}, P. Miranda^{xv}, J. Valdes-Galicia^{xvi}, L. X. Gonzalez^{xvi}, A. Hurtado^{xvi}, and O. Musalem^{xvi}

*, *Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-8601, Japan*
†*Department of Physics, Faculty of Science, Konan University, Kobe 658-8501, Japan*
‡*College of Industrial Technologies, Nihon University, Narashino 275-0005, Japan*
§*Collge of Engineering, Chubu University, Kasugai 487-8501, Japan*
¶*Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan*
$^{\|}$*RIKEN, Wako 351-0198, Japan*
***Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan*
††*National Astronomical Observatory of Japan, Hilo, Hawaii 96720, USA*
‡‡*National Astronomical Observatory of Japan, Mitaka 181-8588, Japan*
^{x}*Department of Physics, Tokyo Institute of Technology, Megro 152-8551, Japan*
^{xi}*Institute of Space and Astronautical Science, JAXA, Sagamihara 229-8510, Japan*
^{xii}*Physikalisches Institut, University of Bern, CH-3012, Bern, Switzerland*
^{xiii}*Yerevan Physics Institute, AM-375036, Yerevan, Armenia*
^{xiv}*Institute of High Energy Physics, Chinese Academy of Science, Beijing 100039, China*
^{xv}*Instituto de Investigaciones Fisicas, UMSA, Casilla 8635, La Paz, Bolivia*
^{xvi}*Instituto de Geofisica, UNAM, Coyoacan DF 04510, Mexico*

***Abstract*. A network of solar neutron telescopes has been developed since the middle of solar cycle 22. We have detected several important solar neutron events until the end of solar cycle 23 using solar neutron telescopes, but the accumulation of more solar neutron events is indispensable to eclucidate the acceleration mechanism of high energy particles. The data of the solar magnetic field with a space resolution of 0.3 arcsec obtained by *Hinode* satellite will be useful to understand solar neutron events more efficiently than during the previous solar cycles. In this paper we discuss the expected scientific results obtained by the world-wide network of solar neutron telescopes during solar cycle 24.**

***Keywords*: solar neutron telescopes, solar cycle 24, world-wide network**

I. INTRODUCTION

It is essential to observe high energy particles associated with solar flares in order to study the acceleration mechanisms of charged particles at the Sun, that will help us to understand the acceleration mechanisms of cosmic rays in general, although the maximum energy attainable for charged particles at the Sun is much lower than those of average cosmic rays. Detecting neutrons produced by charged particles accelerated at the solar surface is useful because neutrons are not deflected by electromagnetic fields around the Sun and also in the interplanetary space, and keep information on the time when they are produced at the Sun. Moreover neutrons are not produced by electrons, but only by ions, which are main components of cosmic rays. It is, however, only seldom possible to detect solar neutrons at the Earth because the neutron flux produced at the Sun is in general too low or neutrons are not directed toward the Earth or energy is not high enough.

We have developed a network of solar neutron telescopes since the middle of solar cycle 22 in order to detect solar neutrons efficiently. The time of flight of neutrons from the Sun to the Earth depends on the energy of a neutron because a neutron has a mass. It is essential for us to know when neutrons were produced at the Sun in order to understand the acceleration mechanisms of ions. Therefore a solar neutron telescope is designed to measure the energy of neutrons in order for us to infer the time profile of the production of neutrons at the Sun from the observed time profile of neutrons at the detector. Seven solar neutron telescopes are placed at high altitudes and at different longitudes to cover 24 hour observation of stochastic solar neutron events, which are attenuated in the atmosphere. These seven high altitude stations are, Norikura (Japan [1]), Yanbajing (Tibet [2]), Aragats (Armenia [3]), Gornergrat (Switzerland [4]), Chacaltaya (Bolivia [5]), Sierra Negra (Mexico [6]), and Mauna Kea (USA [7]). The location, the area of the detector, and the cut-off rigidity of each station are summarized in Table 1 of [8]. We have kept operating these solar neutron telescopes and detected several solar neutron events during solar cycle 23. In the case of the solar neutron event on September 7, 2005, solar neutrons were detected by both solar neutron telescopes in Bolivia and Mexico together with two neutron monitors there [11]. It is expected that more solar neutron events will be detected during solar cycle 24.

II. Expected performance of solar neutron telescopes in solar cycle 24

We discuss in this section the scientific achievement related with the acceleration mechanisms of ions which will be expected to be obtained by the network of solar neutron telescopes in solar cycle 24.

A. Acceleration of protons and electrons

Although a neutron is a probe to understand the acceleration mechanisms of ions, it is important to compare neutron with the probe of the electron acceleration in order to know if the same acceleration works on both ions and electrons, or not. The Sun is almost always observed by various electromagnetic waves, from radio to gamma rays, and we can usually investigate if there are any differences between the acceleration of protons and electrons for solar neutron events. Some of the solar neutron events observed during solar cycle 23 can be explained if we assume that neutrons were produced with the same time profiles as hard X-rays and/or gamma rays [9] [10]. On the other hand, in the case of the solar flare on September 7, 2005, we cannot explain the time profile of solar neutrons detected on the ground assuming that neutrons were produced with the same time profile as hard X-rays [11] [12]. It is clearly shown that neutrons are produced at the Sun for a longer duration than hard X-rays and gamma rays. It is indicated that ions were either accelerated or trapped longer than electrons in the emission site of neutrons. We usually assume some trapping model to investigate if the particular trapping model can explain the time profile of observed neutral particles (As for the flare on September 7, 2005, see for example [13]). Rank et al. [14] discussed the possibility of explaining the long duration solar gamma ray event on June 11, 1991 either by a long acceleration or a long trapping, by assuming several models with some appropriate parameters, such as the length of the magnetic loop, pitch angle and so on. They concluded that the event cannot be explained by a long trapping of charged particles for the parameters they examined.

In order to discriminate if ions are accelerated longer than electrons, or ions are trapped at the emission site of neutrons longer than electrons at the emission site of hard X-rays or bremsstrahlung gamma rays, detailed information on the structure of the magnetic field is important. The solar optical telescope (SOT) onboard *Hinode* satellite, which was launched on September 23, 2006, has a space resolution better than 0.3 arcsec [15], much smaller than the size of a sunspot. It is expected that this will give the realistic geometry of the magnetic loop to conclude if charged particles could be accelerated, or trapped for a long time. When we have a next gigantic solar flare with the emission of hard X-rays, gamma rays, and neutrons, the acceleration of electrons and protons will be studied more profoundly with the information of the detailed structure of the magnetic field.

B. The energy spectrum of solar neutrons

The information on the energy spectrum of solar neutrons is quite decisive to determine what kind of acceleration is working at the Sun. The expected energy spectra of neutrons depend on the acceleration models as shown by several authors. The energy spectrum of neutrons follows a power law in the case of the shock acceleration, but it is a Bessel function in the case of the stochastic acceleration [16] [17].

It is, however, difficult to determine if the shape of the energy spectrum of neutrons is a power law or a Bessel function, because the Bessel function looks like a power law if the energy range of neutrons is narrow (See Figure 8 in [17] for example). In the case of the solar neutron telescopes, we adopt several discrimination levels for the energy of neutrons, and measure a counting rate of neutrons exceeding each threshold energy. The maximum threshold energy for neutrons that we adopt for the solar neutron telescope is 300 MeV at the moment. On the other hand, neutrons with energies less than 100 MeV are severely attenuated in the Earth's atmosphere as shown in Fig. 1 [18]. Therefore the energy by which we derive the energy spectrum of neutrons ranges from 100 MeV to 300 MeV, which is too narrow to derive the energy spectrum of neutrons precisely. In order to extend this energy range, it is necessary to increase the energy threshold adopted for solar neutron telescopes, or to use the data of solar neutrons with energies less than 100 MeV measured in the space.

There is one appropriate detector to measure solar neutrons with energies less than 100 MeV in solar cycle 24. It is the Scintillation Fiber Detector (FIB), which is one of the Space Environment Data Acquisition equipment (SEDA-AP) in the Japanese Experiment Module (JEM) onboard the International Space Station [19]. It is sensitive to neutrons from 15 MeV to 100 MeV. SEDA-AP is expected to start in 2009. The sensitivity of the scintillation fiber detector has been estimated by Imaida et al. [20] for the solar neutron event which has the same intensity as the one observed on June 4, 1991. In this event, neutrons were detected both by the prototype of the Norikura solar neutron telescope [21] and by the Oriented Scintillation Spectrometer Experiment (OSSE) onboard the Compton Gamma Ray Observatory (CGRO) [22]. The same figure as Figure 25 in [20] is shown in Fig. 2. The counting rate of solar neutrons is

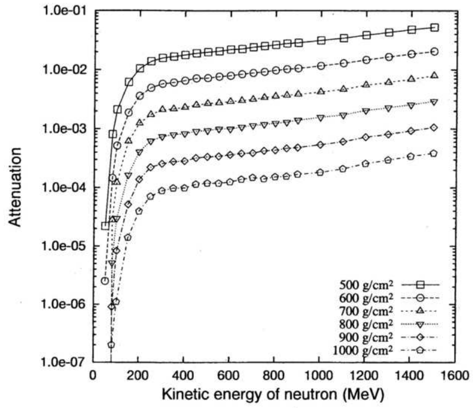

Fig. 1. The attenuation of neutrons in the atmosphere as a function of the energy of neutrons at various altitude [18].

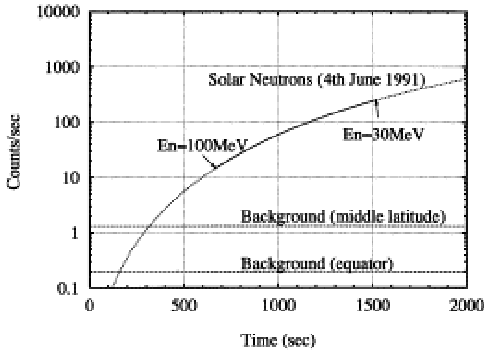

Fig. 2. The same figure as Figure 25 in [20]. The detailed explanation of the figure is given in the text.

shown by the curved line as a function of time of arrival at the Earth with respect to the light signals. Neutrons of all energies are assumed to have been produced at once at the Sun with the energy spectrum of the power –4.8. The horizontal dashed lines show the expected quiescent background based on the data of Russian group [23]. It should be noted that the energy of recoil protons from the incident neutrons are measuread with an energy resolution better than 10 % [20].

The sensitivity of FIB is much better than the ground-based solar neutron telescopes if the energy spectrum of neutrons follows a power law with the power –5 $\sim$ –4. Therefore it is expected that most solar neutron events will be covered by a wide range of the energy of neutrons in solar cycle 24. The shape of the energy spectrum of neutrons will be determined precisely and the acceleration mechanisms of ions will be understood more profoundly.

C. The place where particles are accelerated

When neutrons are produced in the atmosphere of the Sun, their directions are concentrated in the direction of accelerated ions. Therefore it is correct to say that some of accelerated ions were moving towards the Earth when neutrons were observed at the detectors on the Earth. The position of solar flares where neutrons are produced may

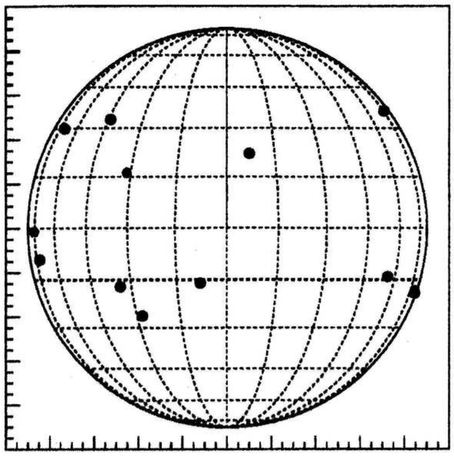

Fig. 3. The position of solar flares for which solar neutrons were detected up to the end of solar cycle 23 (revised from [26]).

indicate the direction of acceleration with regard to the solar surface or the structure of the magnetic field. For example, if nuclear reactions are always produced by charged particles as they slow down deep in the solar atmosphere, it is unlikely that we see solar neutrons except for a limb flare. On the other hand, if ions are accelerated or escaped from the acceleration region towards corona, neutrons are produced at a remote place from the solar surface. In this case, the visibility of solar neutrons is rather indifferent to the position of the flare viewd from the Earth. The production of neutral particles at different sites and different directions of ions is discussed in detail in terms of a thick target model and a thin target model in [24] [25]. The position of solar flares for which solar neutrons were detected is plotted in Fig. 3. This is a modified version of Figure 9.1 of [26], with two new solar neutron events [11] [27] added. The postion of solar neutron events is rather isotropic in longitude. The knowledge of the detailed structure of the magnetic field for each solar flare, however, is necessary to discuss this result in the light of acceleration. The relation beween the position of solar flare and the production of solar neutrons will be discussed more in detail in solar cycle 24 with the data of the magnetic fields obtained by *Hinode*.

D. Solar proton events

All 7 solar neutron telescopes are at locations where the cut-off rigidity of charged particles is high (See Table 1 in [8]) even exceeding 10 GV. Therefore in the case that an increased counting rate is recorded by the solar neutron telescopes, the existence of solar cosmic rays with very high energies can be identified, and the energy spectrum of the charged particles at its higher end can be derived. The fact that we are measuring originally very high energy particles will be useful for a Ground Level Enhancement event to know the maximum energy of the acceleration even if neutrons are not detected.

In this respect, the global solar neutron telescope network complements the worldwide network of neutron monitors.

III. Summary

The first sunspot observed in January 2008 with inverse magnetic polarity gives evidence that solar cycle 24 has started, and solar cycle 24 is expected to have its maximum activity around 2012. The world-wide network of solar neutron telescopes is ready for observing solar neutrons. At the same time, the data of *Hinode* satellite will give the precise structure of the magnetic field with a space resolution better than 0.3 arcsec. This is important to know how ions are accelerated or trapped at the Sun. Moreover the data from FIB onboard the International Space Station will give the energy spectrum of neutrons with energies < 100 MeV. It is expected that the energy spectrum of solar neutrons and the relation between ion acceleration and electron acceleration will be clarified during solar cycle 24.

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