Propagation of solar-neutron decay electrons in the interplanetary magnetic field

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Summary. — In solar flares, accelerated ions undergo nuclear interactions in the solar atmosphere. In these interactions high-energy neutrons are produced and emitted into the interplanetary space. In this paper, the author will discuss several prominent characteristics of electrons produced by the decay of solar neutrons. Calculations are given which show that solar-neutron decay electrons will bring us unique information on the total amount of produced neutrons. Properties of solar-neutron decay electrons are investigated exhaustively by numerical simulations. After a neutron decays in interplanetary space, the electron trajectory has been traced along the magnetic field, taking the electron pitch angle scattering into account. Our calculations show that these electrons can be detected in a properly prepared electron detector if solar flares occur in a region of solar surface from the central to western limb of the Sun. It is predicted that the electron flux will be enhanced when the interplanetary magnetic field is connected to the Sun at its minimum distance from the solar surface. It is predicted that the energy spectrum of solar neutron decay electrons is significantly peaked at around 400 keV, and as such, the neutron contribution to the spectrum can be easily identified from background electrons and/or directly accelerated electrons in the flares.

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1. – Introduction

The existence of solar neutrons, which are produced by nuclear interactions between accelerated ions and solar atmospheric nucleons in the solar flares, was first pointed out by Biermann *et al.* (1951). Solar neutrons are considered to bring us important knowledge on particle acceleration mechanisms in flares, since solar neutrons can propagate in the interplanetary magnetic field without any reflection. The intensity and the energy spectrum of solar neutrons in solar atmosphere and also on the Earth orbit were first calculated by Lingenfelter *et al.* (1965*a,b*). They concluded that it might be possible to observe solar neutrons near the Earth. After their work, many calculations on the production of solar neutrons have been done (*e.g.*, Hua and Lingenfelter, 1987; Ramaty and Murphy, 1987; Murphy *et al.*, 1987).

The first reliable detection of solar neutrons was accomplished by the GRS detector on board the SMM spacecraft for the flare on June 21, 1980 (Chupp *et al.*, 1982). Solar neutrons were observed by the GRS detector again in association with the solar flare on June 3, 1982. At the same time, excess counts due to solar neutrons were also observed by neutron monitors located near the sub-solar point (Chupp *et al.*, 1987, and references therein). These observations were made during solar cycle 21. In solar cycle 22, there were also several observations of solar neutrons. Debrunner *et al.* (1993) reported that the flare on May 24, 1990 is the biggest flare in solar neutrons. The neutron emissivity of this flare is 30 times lager than the flare on June 3, 1982. For the flare on June 4, 1991, Muraki *et al.* (1992) succeeded to observe solar neutrons using a new type of solar-neutron detector which could measure neutron energy. However, observations of solar neutrons are still sparse and statistics are not enough to understand the particle acceleration mechanism of solar flare.

A free neutron has a mean lifetime of 887 ± 2 s. A proton, electron and anti-electron-neutrino are produced in the beta-decay of a neutron. A significant fraction of solar neutrons decay into the above particles before reaching the Earth. Thus many decay products are produced in the interplanetary space. Instead of the direct detection of solar neutrons, the observation of charged decay products from solar neutrons must be taken into account. Through observation of these charged decay products, we can obtain fruitful information not only about solar neutrons but also on the propagation of charged particles in the interplanetary space.

The rest mass of a proton (938.3 MeV) is nearly the same as that of a neutron (939.6 MeV), hence from momentum conservation, the energy of the daughter proton in the neutron decay process is nearly the same as the parent neutron. This implies that the energy spectrum of solar neutrons can be estimated from the observation of neutron decay protons (NDPs). Most low-energy solar neutrons decay before reaching the Earth. Only a few percent of solar neutrons with energy 10 MeV survive. We can obtain the energy spectrum of low-energy solar neutrons more easily by the observation of NDPs rather than the direct neutrons observation.

The propagation of NDPs in the interplanetary magnetic field was first calculated by *Roelof* [1966] using a simple isotropic diffusion model. Actual detection of NDPs was first reported by Evenson *et al.* (1983); these DDPs were associated with a flare on June 3, 1982. Recently, a more complete calculation of the propagation of NDPs was carried out by Ruffolo (1991). He applied his calculation to the NDP events on June 3, 1982 and April 24, 1984. Energy spectra and emissivity of solar neutrons were derived from the data of NDPs in those events. Under each condition of interplanetary space, the mean free path of protons along the field line was also determined very accurately.

The possibility of solar-neutron detection using a different decay channel such as neutron decay electrons (NDEs) has also been discussed. Daibog and Stolpovskii (1987) estimated NDE fluxes and mentioned that the total number of solar neutrons could be estimated from the observation of NDEs. They also reported two possible events of NDEs in their paper. However, their calculation was based only on the elementary diffusion equation for the propagation of NDEs and they have assumed that all NDEs have the same velocity. The authors concluded that their observations have not confirmed NDEs. Recently, Dröge *et al.* (1996) reported the observation of NDEs associated with flare on June 21 1980. However, the flare occurred in the western limb of the solar surface, the distinction of NDEs from the solar directory accelarated electrons is not clear as these authors suggested.

Here, we would like to search for evidence of solar-neutron production through the electron channel. The study should be used not only in the search for experimental evidence, but also in numerical simulations. In the former case, we reported unusual bumping of electron flux after a solar flare on October 19 1989 (Koi *et al.*, 1993). Furthermore, we have continued the search for electron excesses from the solar neutrons using the GEOTAIL satellite HEP-LD sensor. However, after the launch of GEOTAIL, there was a reduced solar activity. We are just waiting for the next solar cycle 23. In the latter case, a calculation of the propagation of NDEs in interplanetary space is carried out taking into account many parameters, for example, the energy spectrum of solar neutrons, flare location in relation with interplanetary magnetic field and so on. In sect. **2**, we explain our calculation in detail. We show results of the calculation in sect. **3** and a new identification method to distinguish NDEs from other solar energetic electrons and background sources is also proposed. The possibility of observing NDEs is discussed in sect. **4**.

2. – Basic assumptions and methods for numerical calculation

In this section we describe our basic assumptions and methods of our numerical calculations. Before entering detailed descriptions of each element, we summarize here the outline of the production and propagation of NDEs in the interplanetary space. When a large flare occurs, solar neutrons are produced in the solar atmosphere near the flare region. Those neutrons are produced in collisions between accelerated ions and atmospheric nucleons. Later we show that the energy spectrum of solar neutrons plays an important role in our calculation. However, the shape of the spectrum has not yet been established by observation. Thus, two types of energy spectra are assumed in the calculation. Neutrons are not affected by the interplanetary magnetic field and fly straightly forward. NDEs are produced by the decay of these flying neutrons in the interplanetary space. When neutrons decay, their daughter electrons have a broad energy distribution. This energy distribution of the electrons must be considered in production function of NDEs. After their production in the interplanetary space, the NDEs are affected by the magnetic field and travel along the field line. Therefore, when neutrons decay on the field line connected to the Earth, these daughter electrons can be transported to the observation point. Depending on the location of flare, a large part of the observer's field line is hidden from the neutrons producing point by the solar surface. We consider this effect in subsect. **2**˙3. NDEs propagate along the field line with its pitch angle changing by small perturbations and focusing of the magnetic field. The intensity and time profile of NDEs at the observation point are influenced by this effect. Finally, we refer to the initial and boundary conditions of our calculation.

2˙1. *Energy spectrum of solar neutrons.* – As mentioned before, the electrons from the decay of neutrons have a broad energy distribution. In other words, the same energy electrons could be produced from different energy neutrons. Even if we calculate the propagation of NDEs at a fixed energy, such energy electrons could be produced from the decay of solar neutrons with a wide energy region. One must assume an energy spectrum of parent solar neutrons in order to obtain the production function of NDEs in interplanetary space.

There are several observations of solar-neutron events. In those events, the energy spectrum has been obtained. For in stance, Chupp *et al.* (1987) derived a power law index (s) of -2.4 for solar neutrons with energies greater than 100 MeV. This result was obtained with use of the GRS on board SMM and neutron monitors. Ruffolo (1991) derived $s = -1.7$ for solar neutrons with energies between 26.5 MeV and 147 MeV from the flare. This result was based on NDP data. A bending of the energy spectrum was suggested by this result.

There are also several Monte Carlo simulations on the production of solar neutrons in the solar atmosphere (*e.g.*, Lingenfelter *et al.* 1965*a*; Ramaty and Murphy, 1987). A hardening of solar-neutron energy spectra in the lower-energy region was also shown in the results of these Monte Carlo simulations.

An interesting simulation of solar neutrons was also presented by *Hua and Lingenfelter* in 1987. Their simulation included not only solar-neutrons production in the solar atmosphere but also the process involving escape to interplanetary space.

An curious feature was shown in the energy spectrum of escaping solar neutrons. It was shown that escaping neutrons are more intense than produced neutrons at low energies ($<$ 10MeV). This interesting result comes from the backscattering effects of higher-energy neutrons which were initially directed downward. The direct observation of solar neutrons in such low-energy region is very difficult. Even through the NDP channel, there are no reports of observations of solar neutrons under 20 MeV. The present NDE method can measure the number of solar neutrons from a low-energy range, though each neutron energy cannot be determined. The energy spectrum of solar neutrons at the production is not yet well understood. The data on solar neutrons with less than 20 MeV are very sparse owing to in-flight neutron decay. One of the purposes of this paper is to show how to obtain the energy spectrum of such low-energy solar neutrons.

In the current simulations, two types of energy spectra of solar neutrons are considered. One model has a power law spectrum. The power law index of this model is $s = -2.4$ over the full energy range. This model is referred to as the single power law model. The other model also takes a power law form but the value of the index changes at 100 MeV. The index is $s = -2.4$ above 100 MeV and -1.4 below 100 MeV. This model is referred to as the double power law model. The maximum energy of solar neutrons is taken to be 2 GeV in both models. There is some possibility of production of higher-energy neutrons, but their fluxes are expected to be very low and we have neglected them. Because of gravitational trapping of solar neutrons by the Sun, the minimum energy of solar neutrons is taken at 2 keV for both models. The emissivity of solar neutrons at solar surface is normalized at 100 MeV in both models.

2˙2. *Energy distribution of electrons from β-decay of neutrons.* – In order to obtain the production function of NDEs in the interplanetary space, the energy and momentum distribution of electrons from β-decay of neutrons must be calculated precisely. Since neutron β-decay is a three-body decay, the energies of the daughter particles are not uniquely determined. In the neutron rest system, the energy corresponding to the Q-value is divided among three daughter particles after the decay. The Q-value of β-decay of neutron is 0.78 MeV. Taking account of the phase space of each particle under energy and momentum conservation, the energy distributions of decay products from neutrons at rest are calculated. Regardless of energies and kinds of decay products, the momentum distributions of these products are isotropic. The energy distributions for decay products from a moving neutron are available from a Lorentz transform of their phase space density. Because of the isotropic momentum distributions in the flame of a neutron at rest, the momentum distributions of these particles are axial-symmetric. The direction of the symmetric axis is parallel to the momentum vector of the neutron.

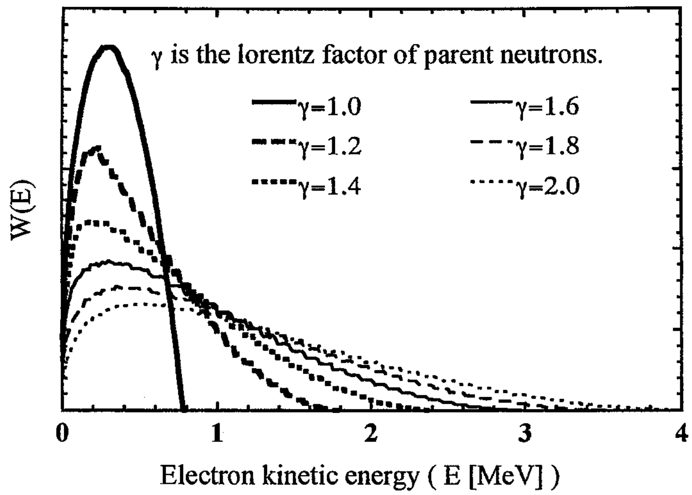

Fig. 1. – The energy distribution of electrons from neutrons decay. The γ factor represents the Lorentz factor of parent neutrons.

The energy distribution of electrons from the decay of neutrons is shown in fig. 1. The Lorentz factor of the parent neutrons is denoted by the parameter γ. It is worthwhile to note that even if the Lorentz factor of the parent neutrons changes from 1.0 to 1.2, the energy distribution of the daughter electrons does not change significantly in shape. Most solar neutrons have Lorentz factors lower than 1.2 (neutron kinetic energy of 188 MeV), thus most daughter electrons should have a similar energy distribution. This is one of the characteristics of solar-neutron decay electrons.

2˙3. *Neutron horizon effect.* – When solar neutrons decay on the interplanetary magnetic field lines which are connected to the observer, NDPs and NDEs are transported to the observation point. Therefore the flare location in relation to the observer's field line is important. If a flare occurs at the eastern limb of the Sun, a large part of the observer's field line is shadowed from neutrons by the solar surface (fig. 2). This shadowing effect is known to us as the neutron horizon effect.

Roelof (1966) did not take account of this effect in his calculation of NDPs, first introduced by Evenson *et al.* (1983). Our calculation also includes this effect in the production function of NDEs.

A parameter, $R_{\min}$, is defined as the closest distance between the flare and the unshadowed observer's field line. The relation between $R_{\min}$ and the flare location on the Sun is determined by the configuration of the interplanetary magnetic field. The Parker spiral magnetic-field model with solar wind velocity of 450 km/s is used in our calculation. Therefore, $R_{\min}$ becomes large when the flare occurs at the eastern limb of the Sun and becomes small when the flare occurs at the western limb. However, the magnetic field may have a more complicated structure than the Parker spiral near the Sun. We consider the possibility that there are closed magnetic fields near the flare region and magnetic field lines which open to the interplanetary space away from the flare region. When $R_{\min}$, derived from the shadowing effect by the solar surface, is small, such a separation between the flare and the open field line connecting it to the observer may become more important

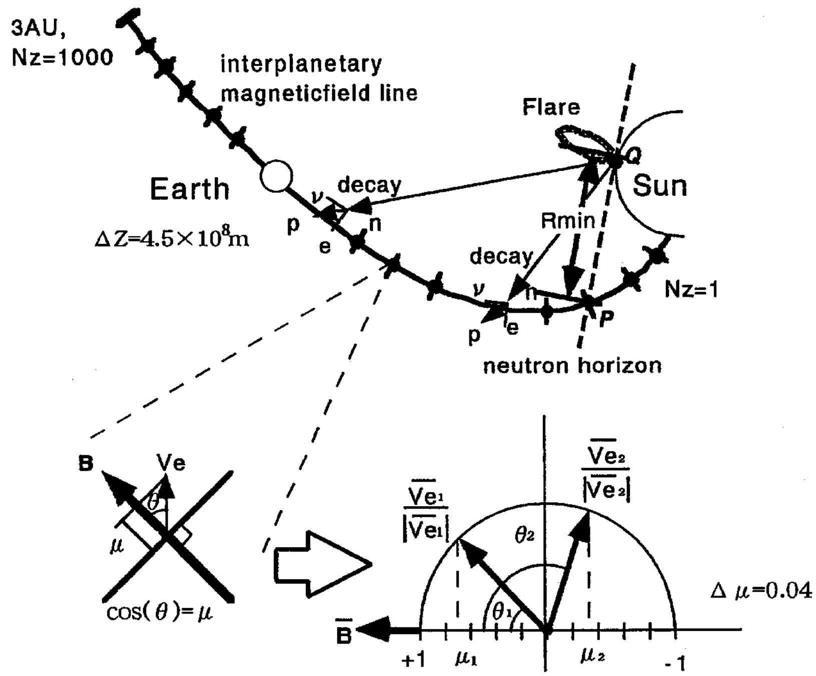

Fig. 2. – A schematic of our simulation model.

than the simple geometrical $R_{\rm min}$. Therefore, we limit the minimum value of $R_{\rm min}$ to 2.5 $R_\odot$. This value comes from the solar potential field model (Schatten *et al.* 1969; Hoeksema *et al.* 1986), where a radial magnetic field continuously appears above the height.

2'4. *Transportation of charged particles in the interplanetary space.* – Once NDEs are produced in the interplanetary space, they propagate along the interplanetary magnetic field. As mentioned before, the Parker spiral magnetic field was used as the model for large-scale interplanetary magnetic field in the present calculation. The small-scale turbulence in the magnetic field which causes the pitch angle scattering of charged particles is also considered in the calculation. To simulate the propagation of charged particles in such a magnetic field, the following equations are used by many former researchers (*e.g.*, Roelof, 1969; Bieber *et al.*, 1980; Ng and Wong, 1983).

$$\frac{\partial F(t,\mu,z)}{\partial t} = -\mu v \frac{\partial F(t,\mu,z)}{\partial z} - \frac{\partial}{\partial \mu} S_\mu(t,\mu,z) + Q(t,\mu,z)\,,$$

$$S_\mu(t,\mu,z) \equiv -\frac{\varphi(\mu)}{2}\frac{F(t,\mu,z)}{\partial \mu} + \frac{v}{2L(z)}(1-\mu^2)F(t,\mu,z)\,.$$

$F(t,\mu,z)$ is the distribution function of particles as a function of time t. μ represents the pitch angle cosine, z the arclength along the magnetic field, S_μ is the flux of μ, Q is the production function of NDEs, φ is the diffusion coefficient for pitch angle scattering and L is the focusing length.

The value of the production function $Q(t, \mu, z)$ is calculated as follows. A point z is at a distance r far away from the flare site and the time is t after start of simulation. If r is smaller than R_{min} then $Q(t, \mu, z)$ is equal to 0 for all t and μ. The impulsive production of solar neutrons at $t = 0$ is assumed in our simulation. Therefore, neutrons which have a velocity of $r/t = v_{\mathrm{n}}$ just reach the point.

The energy of these neutrons is calculated from the velocity. According to our assumed energy spectrum of solar neutrons, the emissivity of solar neutrons per MeV per sr is given by

$$N_{\mathrm{n}} = A \left(\frac{E_{\mathrm{n}}}{100} \right)^{s} ,$$

where A is the emissivity at 100 MeV.

The number of neutrons which pass the magnetic flux tube subtending $\Delta\Omega$ from the flare site is given by

$$N_{\mathrm{n}} \exp \left[-\frac{t}{\gamma\tau} \right] \Delta\Omega ,$$

where γ is the Lorentz factor of the neutron and τ is the mean lifetime of the neutron.

The number of decay of these neutrons in the flux tube per length per time is given by

$$N_{\mathrm{n}} \exp \left[-\frac{t}{\gamma\tau} \right] \Delta\Omega \times \frac{1}{\gamma\tau v_{\mathrm{n}}} \frac{\mathrm{d}E_{\mathrm{n}}}{\mathrm{d}v_{\mathrm{n}}} \frac{\mathrm{d}v_{\mathrm{n}}}{\mathrm{d}t}$$

and the same number of electrons N_{e} yield local magnetic flux tube.

The energy and momentum distribution of these electrons have already been discussed in this section. The momentum distribution of electrons from the decay of neutrons which have an energy of E_{n} is calculated. The momentum vector of neutrons makes an angle θ with the local magnetic field line. The pitch angle distribution of the electrons at the point is derived from the rotation of momentum distribution of electrons.

A function $f(E_{\mathrm{n}}, v_{\mathrm{e}}, \mu)$ which gives the ratio of electrons with an energy of v_{e} and a pitch angle of μ to all electrons from decays of neutrons with an energy of E_{n} is introduced. Then the value of the production function $Q(t, \mu, z)$ is determined by

$$Q(t, \mu, z) = N_{\mathrm{e}} \times f(E_{\mathrm{n}}, v_{\mathrm{e}}, \mu).$$

Charged particles propagate along the Parker spiral magnetic field line with a speed of μv, and its pitch angles are changed by small-scale irregularities of the magnetic field and by adiabatic focusing. The pitch angle scattering coefficient φ is assumed to be given by the following equation from the quasilinear theory of Jokipii (1974):

$$\varphi(\mu) = A|\mu|^{q-1}(1 - \mu^2) ,$$

where A is the intensity parameter of the scattering and q is the anisotropy parameter. The parameter A is calculated by the following equation:

$$A = \frac{3v}{\lambda(2 - q)(4 - q)} ,$$

where λ is the mean free path of charged particles in the interplanetary magnetic field. In our calculation 0.1 AU was used for the value of λ except for some calculations noted later and 1.5 was used for the value of q. The value λ changes according to the condition of the interplanetary magnetic field. To determine the influence of a variety of the mean free path we also carry out several calculations changing the λ from 0.02 to 0.5 AU. We used the finite-difference method, applying the operator splitting method for solving the transport equation. Overall the numerical process of our calculations follows the PhD thesis of Ruffolo (1991) which calculated the interplanetary transport of decay protons from solar-flare neutrons.

2·5. *Initial and boundary conditions.* – The initial condition of our calculation is defined as follows. At $t = 0$, there are no particles for all z and μ, *i.e.* background particles in the interplanetary space are not accounted for in our calculation. We assume that the production of solar neutrons occurs at $t = 0$ modeled as a δ-function. Isotropic neutron escape from the Sun is assumed. There are some reports that neutrons production can be sustained over a few tens of minutes (*e.g.*, Chupp *et al.*, 1987; Debrunner *et al.*, 1994). However since the typical decay time of neutron production is 20 s (Kocharov *et al.*, 1994), most neutrons are produced within a minute. On the other hand, the time resolution of our calculation is about a minute or longer. It depends on the velocity of the calculated electrons. So, the δ-function can be used as a substitute for the production of solar neutrons in our calculation.

There are a thousand equally spaced grid points along the interplanetary magnetic field line with the maximum z-grid at 3 AU from the Sun. There are fifty-one grid points between -1.0 and 1.0 for μ.

The following boundary conditions are used in our simulation space: $S_\mu = 0$ for $|\mu| > 1$ is the boundary condition for the μ grid. For the z-grid, particles are allowed to flow out but not in at both ends.

3. – Results of numerical calculation

We have calculated the propagation of NDEs in the interplanetary space, as a function of the energy spectrum of solar neutrons and the value of $R_{\min}$. The results of the calculations are shown in figs. 3-6. The time profiles of intensities of NDEs are shown in the upper panels and the energy spectra of NDEs are shown in lower panel. Both plots are shown as functions of time after solar-neutrons production at the Sun. The parameters used are shown in the top of each panel.

It can be seen that all energy spectra of NDEs have a broad peak at around 400 keV and the high-energy part of the spectrum falls off quickly. Regarding the peak intensity of NDEs, several interesting characteristics can been seen. For the same value of $R_{\min}$, the single power law model gives a higher intensity than the double power law model. For both models, the highest intensities are found for the smallest values of $R_{\min}$. These results are expected in our models. The neutron spectrum is normalized at 100 MeV. The single power law model gives a higher emissivity of neutrons than the double power law model below 100 MeV. As $R_{\min}$ becomes smaller, more neutrons are expected to reach the observer's field line before they decay. This tendency enhances the low-energy neutron flux. It is found that the energy spectrum of solar neutrons and the value of $R_{\min}$ are of critical importance in determining the intensity of NDEs.

Several calculations were carried out in order to understand the effect of the mean free path λ at the peak intensity of NDEs and the time corresponding to maximum intensity.

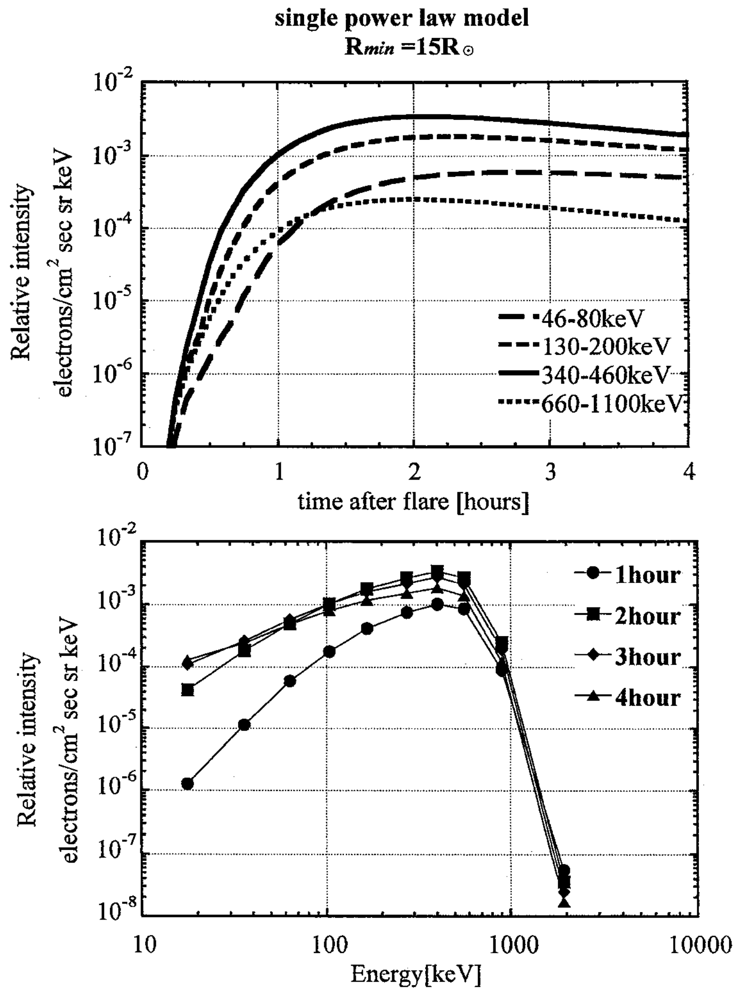

Fig. 3. – Results of the calculations. The adopted energy spectra of solar neutrons for the single power law model with $R_{\rm min} = 15R_\odot$ are shown. The time profiles of NDEs are shown in the upper panel and the evolution of NDEs energy spectra in the lower panel. Regardless of the parameters, all energy spectra have a broad peak around 300–400 keV.

In these calculations, λ was changed from 0.02 AU to 0.5 AU and $R_{\rm min}$ was set at 15 $R_\odot$, 0.3 AU, and 0.68 AU. Both types of energy spectrum are examined but only NDEs within an energy band from 340 to 460 keV are considered. The peak intensities of NDEs for various mean free paths are shown in fig. 7. It can be seen that the peak intensities are slightly shifted for different values of the mean free path. The biggest difference between the two calculations of the same model and same $R_{\rm min}$ is taken to be less than 2.5, which corresponds to a difference of λ between 0.02 and 0.5 in single power law model with $R_{\rm min}$ = 0.68 AU.

The times when the NDE intensities reach their maximum values for various mean free paths are shown in fig. 8. The times of peak intensities are seen earlier for long mean free paths.

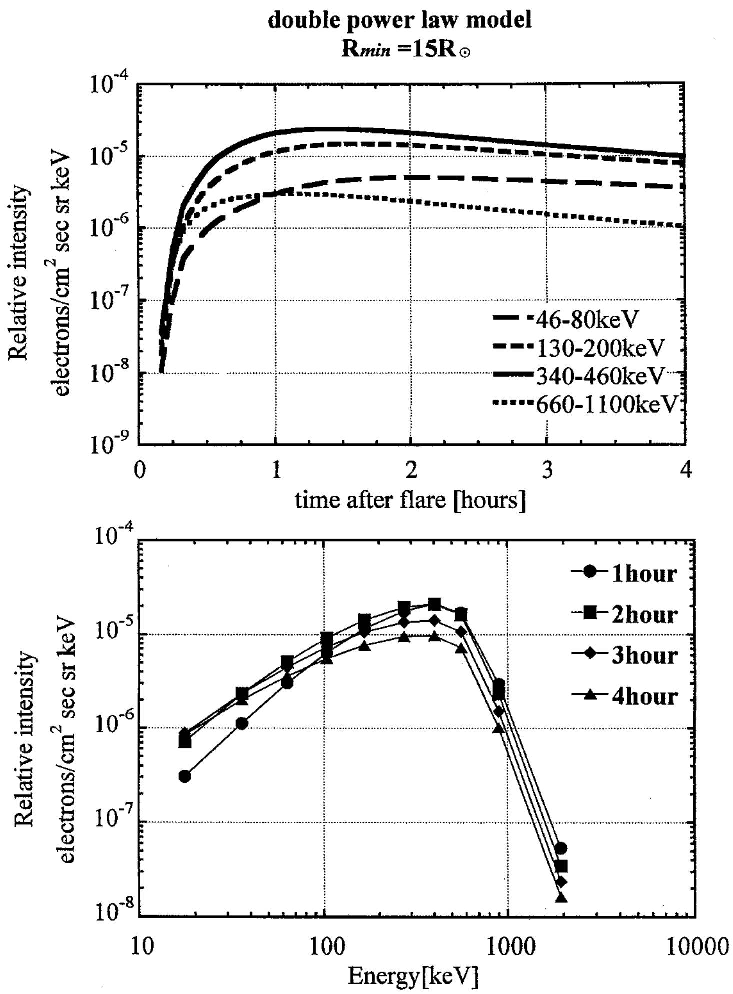

Fig. 4. – Same as fig. 3 but for the double power law model.

It was previously mentioned that our calculations do not include background electrons in the interplanetary space and electrons which are directly accelerated near the flare region. For real measurements of electrons in interplanetary space, these components will also observed at the same time. Thus, the NDE component must be distinguished from these electrons.

If a solar flare occurs at the eastern limb of the solar surface where the interplanetary magnetic field is not connected to the Earth, charged particles which are directly accelerated near the flare region must cross the interplanetary magnetic field lines before it reaches the observer's field line. The mean free path perpendicular to the magnetic field line for the charged particles is very small so that such directly accelerated particles take a long time to reach the Earth. However, neutrons can cross the magnetic field lines freely and reach the region where the field line is connected to the observer. Then, prompt rises of particle intensities created by decay products of those neutrons are observed. This is

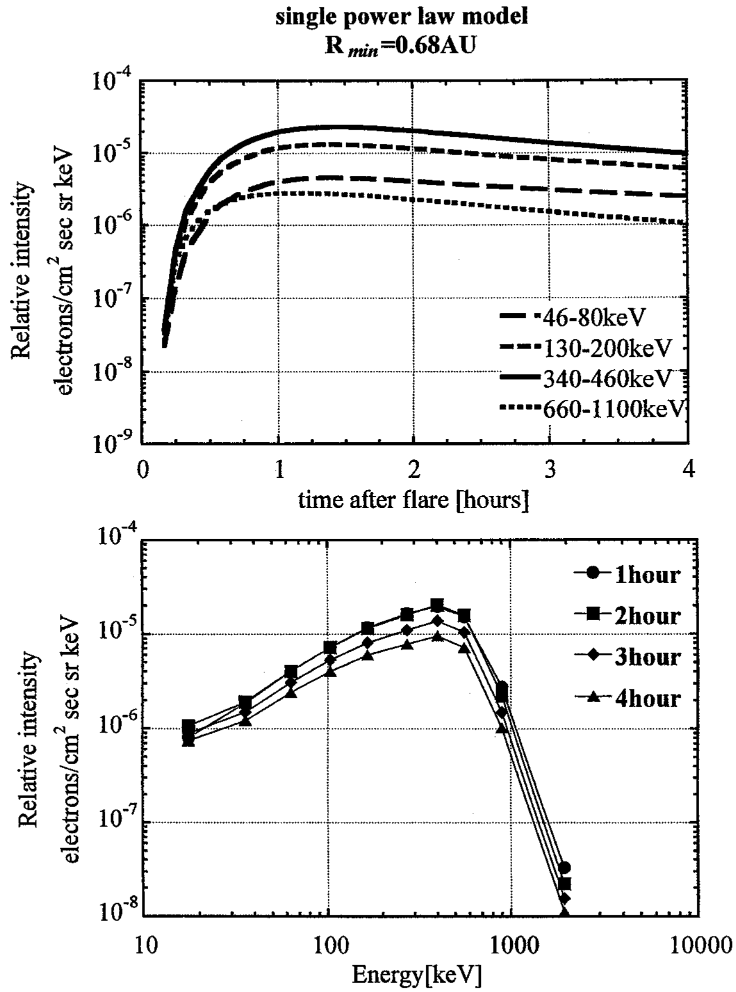

Fig. 5. – Same as fig. 3 but for $R_{\min} = 0.68$ AU.

normally followed by a second much larger increase made by directly accelerated charged particles. Hereafter, we refer to this method of distinguishing between decay products of solar neutrons as the "time profile method". Evenson *et al.* (1983) first succeeded in distinguishing NDPs from directly accelerated protons in neutron flares observed on June 3, 1982 and April 24, 1984 (Evenson *et al.*, 1990) using this method.

When a flare occurs on the solar surface where the magnetic field is connected to the observer, directly accelerated charged particles quickly propagate to the observer. In this case the identification of NDPs and NDEs from directly accelerated charged particles by the time profile method might be difficult.

It was mentioned in this paper that all energy spectra of NDEs have a broad peak around 400 keV and this feature can be used for the detection of NDEs. It is unlikely that interplanetary background electrons and directly accelerated electrons have a peak around this energy. Using this characteristic of NDEs, the measurement of the en-

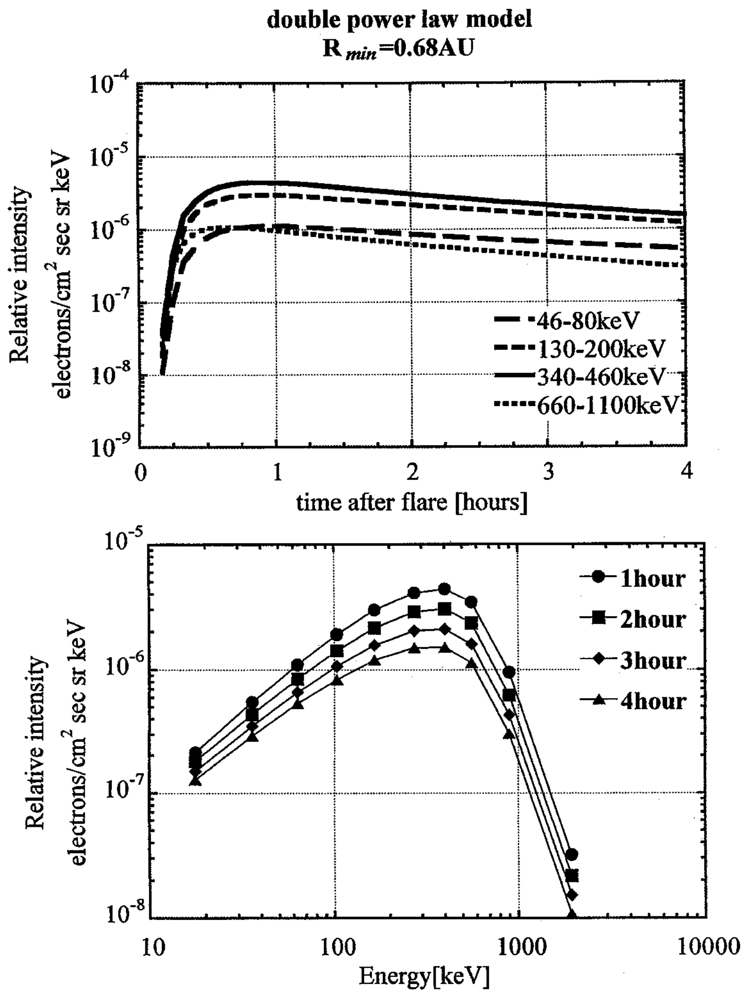

Fig. 6. – Same as fig. 3 but for the double power law model and $R_{\min} = 0.68$ AU.

ergy spectrum of electrons in the interplanetary space allows us to distinguish the NDE component from either the background or directly accelerated electron component. The schematic view of the difference of the present new method is shown in fig. 9b in contrast with the former established model (fig. 9a) by Evenson *et al.* (1983).

The typical energy spectrum of interplanetary electrons in such an energy region obeys a power law. If the NDE component is superimposed on such an energy spectrum, then a shoulder-like structure would appear in the energy spectrum of interplanetary electrons. We shall call this type of identification method for NDEs the "energy spectrum method". Once a part of the NDE spectrum is identified, we can estimate the total number of NDEs and the total number of neutrons.

As previously mentioned, a daughter proton has almost the same energy as the parent neutron. The energy spectrum of solar neutrons is not so different from directly accelerated protons. Therefore, NDPs cannot be discriminated from these protons by the

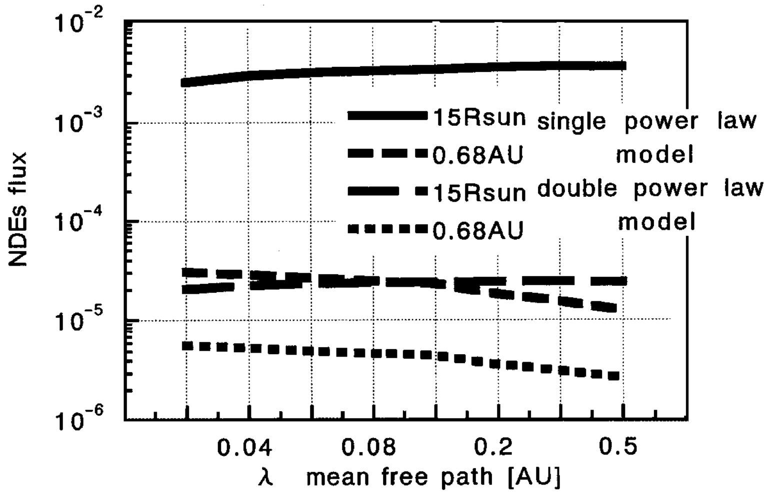

Fig. 7. – The peak intensities of NDEs for various mean free paths.

energy spectrum method. The energy spectrum method can be used only for identifying the NDEs component.

4. – Summary and discussion

We have discussed a method to distinguish NDEs by observation. In order to estimate the intensity of NDEs, one must assume a value for the neutron emissivity at the solar surface. We took this value to be 5.0×10^{26} neutrons/(sr MeV) at 100 MeV which Ruffolo

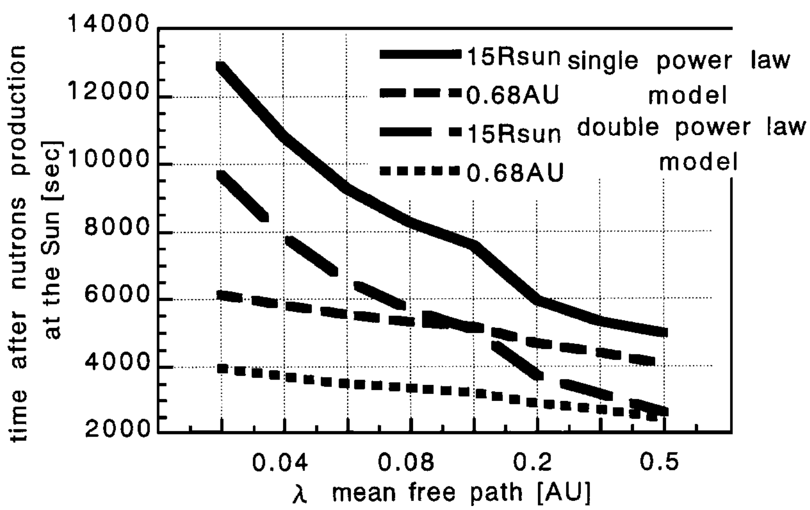

Fig. 8. – The times when the NDE intensities reach their maximum values for various mean free paths. Neutrons are produced at $t = 0$ in solar atmosphere. The light travels from the Sun to the Earth is about 500 seconds.

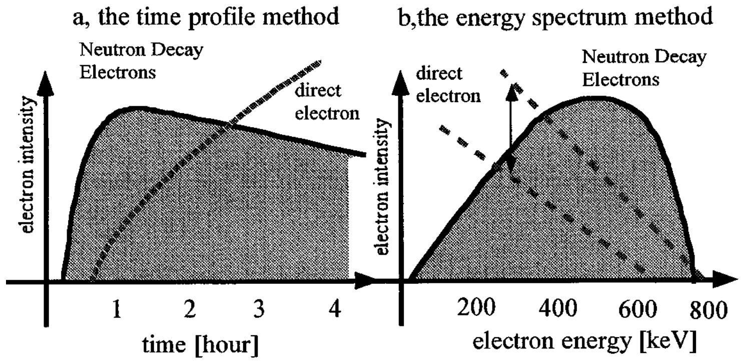

Fig. 9. – A schematic of the methods of distinguishing NDEs from other electrons. For (a) the time profile method and for (b) the energy spectrum method.

(1991) derived from the observation of NDPs associated with the flare on June 3 1982. The energy spectra of solar neutrons are given by power laws.

The intensity of NDEs is strongly dependent on the distance from the production region to the observer's magnetic field. In other words, the location of the flare at the solar surface is very critical for the intensity of NDEs. We estimate the absolute intensity of NDEs interplanetary space near the Earth. The result is shown in fig. 10.

If the energy spectrum of neutrons is represented by a single power law model, then when a flare with a neutron emissivity as strong as the flare on June 3 1982 occurs at the west limb, NDEs should be observed. In this case, the energy spectrum method would

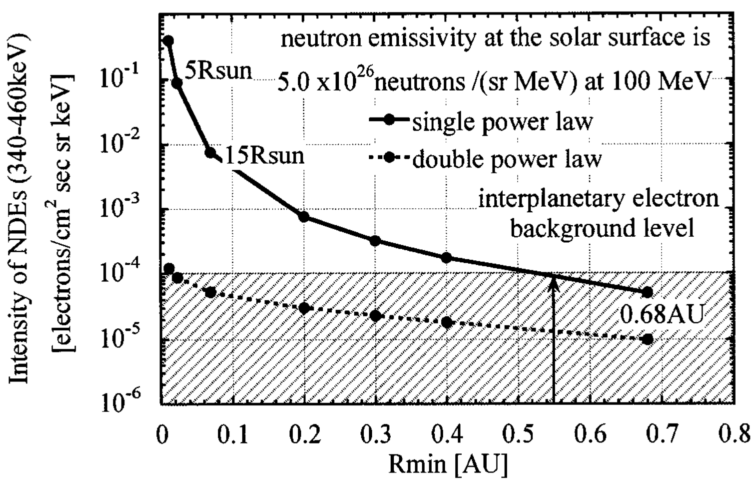

Fig. 10. – Estimation of the absolute intensity of NDEs. The vertical axis represents the absolute maximum intensity of NDEs and the abscissa is the value of R_{min}. Solid and dashed lines represent the adopted solar-neutron energy spectra for double and single power law models. The intensity of background electrons in interplanetary space obtained by earlier observations are represented as the hatched area. This value dramatically changes according to conditions in the interplanetary space.

be necessary for identifying components of the NDEs. If the double power law model is valid for initial neutron production, we need a very strong neutron emissivity for the observation of NDEs, say, ten times larger emissivity than that of flare on June 3, 1982, or a very small value of $R_{\min}$. Our results are consistent with no report of detection of NDEs in association with the flare on June 3, 1982, because the flare occurred at the eastern limb (E72°).

Debrunner *et al.* (1994) reported that the neutron emissivity of the solar flare on May 24 1990 is 30 times greater than that of the flare on June 3 1982. In this case even if the actual neutron energy spectrum takes on a double power law model, there is a possibility to observe NDEs.

Our results of calculations are not consistent with the letter of Daibog and Stolpovskii (1987) which referred to observation of NDEs. In their figs. 3 and 4, the intensity of electrons at 70 to 170 keV was higher than the intensity between 170 and 300 keV. The energy spectra of "observed" electrons is different from our results.

Here we examine a detector suitable for observation of NDEs. The energy spectrum method is useful to distinguish NDEs from other electrons. Thus the detector must be able to measure the electron energies, so the energy range of the detector must include the energy region from a few tens keV to 1 MeV.

It requires sufficient counts of electrons to obtain the energy spectrum of electrons. The number of electrons which arrive in the detector is determined not only by the intensity of electrons (I_{NDEs}) but also by the geometrical factor of the detector (G_{detector}). These electrons are accumulated in some observation period and divided into energy bins which have some energy width. The accumulation time ($T_{\mathrm{accumulation}}$) and the width of the energy bin ($W_{\mathrm{energy\ bin}}$) also determine the number of electrons ($N_{\mathrm{electrons}}$) which we can use for analyzing the energy spectrum. These relationships are expressed by this equation:

$$N_{\mathrm{electron}} = I_{\mathrm{NDEs}} \times G_{\mathrm{detector}} \times T_{\mathrm{accumulation}} \times W_{\mathrm{energy\ bin}} \,.$$

When we require the following observation condition that the intensity of NDEs is 1.0×10^4 (counts / cm^2 s sr keV), the accumulation time is 30 minutes ($= 1.8 \times 10^3$ s), the width of energy bin is 100 keV, and at least ten electrons for each energy bins, then the geometrical factor of detector has to be greater than 5.6×10^{-1} (cm^{2}sr). This value is obtainable for the present scale of detectors that are onboard spacecraft. For example, GEOTAIL, one of the current operational spacecraft, has three detectors which have a geometrical factor of 7.6×10^{-1} (cm^{2}sr) (Doke *et al.*, 1994).

If the accumulation time is extended to 1 hour, then the required geometrical factor becomes half. If we require double the electron counts, for better statistical accuracy, then the required geometrical factor must also be double.

We also consider a flare which is suitable for observation of NDEs. It is generally accepted that solar neutrons are generated by impulsive flares. From the observation of particles at 1 AU, such a flare is called an electron-rich flare. The distribution width on the solar longitude of impulsive flares with which energetic electrons can be observed at 1 AU is only less than 30 degrees with the main contribution coming from the variation of solar wind velocity (Reames, 1994). So the actual emitted cone of impulsive flare is likely to be smaller than the value. When a spacecraft is distant from the cone, the intensity of direct accelerated electrons decreases quickly. Then flares occurring the at disk center are better suited for observation of NDEs than flares at the western limb. The $R_{\min}$ values which determine the intensity of NDEs are almost the same for disk center and western limb. However, the intensity of directly accelerated electrons is lower for the disk flare than for the western-limb flare.

Here we stress again the advantage of identification of NDEs by using the energy spectrum method. The energy spectrum of NDEs has a broad peak at 400 keV and the intensity of NDEs at 50 keV and 1 MeV have almost the same value. The energy spectrum of directly accelerated electrons is approximately expressed by a power law. If the power law index of the energy spectrum of directly accelerated electrons has a value of -2, its intensity at 1 MeV is 400 times less than that of the intensity at 50 keV. When the power law index changes to -3, the difference between the intensity between 50 keV and 1 MeV becomes a factor of 8000. Therefore, we can identify NDEs from directly accelerated electrons at the energy region where the intensity of directly accelerated electrons is low. Once the intensity of NDEs is decided at some energy region, we then know how many NDEs are hidden under directly accelerated electrons over the full energy region. Thus, the total number of solar neutrons can be estimated from the total number of NDEs.

The observation of NDEs gives us unique information on the total number of solar neutrons and thus it makes this a unique observational probe on the production of low-energy solar neutrons. If we observe solar neutrons, NDPs and NDEs simultaneously, we compare these results with each other. For example, the minimum energy of produced solar neutrons may be found in comparison with the energy spectrum of solar neutrons derived from the observation of NDPs and total number of solar neutrons derived from the observation of NDEs.

Other important science is the study of γ-rays. When a neutron is captured by a solar atmospheric proton, a γ-ray with an energy of 2.2 MeV is emitted. If we can compare the intensity of NDEs and 2.2 MeV γ-rays line from the same flare, we know the escape probability of low-energy neutrons to outer solar atmosphere. The angular distribution of parent ions which produce solar neutrons is reflected in this value.

Finally, we would like to mention here that in studying the energy spectrum of interplanetary electrons several hours after big flares, NDEs may be discovered from past satellite data. Then our knowledge of solar neutrons and their decay products would increase significantly and this information would help us not only for solar physics but also for the physics of particles in interplanetary space.

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