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Detecting solar neutrino flares and flavors

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Abstract: Intense solar flares originated in sun spots produce high energy particles (protons, α) well observable by satellites and ground-based detectors. The flare onset produces signals in different energy bands (radio, X, *gamma* and neutrons). The most powerful solar flares as the ones occurred on 23 February 1956, 29 September 1989 and the more recent on October 28th, and the 2nd, 4th, 13th of November 2003 released in sharp times the largest flare energies ($E_{FL} \simeq 10^{31} \div 10^{32}$ erg). The high energy protons in the flare scatter within the solar corona and they must be source of a prompt neutrino burst produced by the decay of charged pions. Later on, solar flare particles hitting the terrestrial atmosphere may marginally increase the atmospheric neutrino flux. The prompt solar neutrino flare may be detected in the largest underground ν detectors. Our estimate for the October-November 2003 solar flares gives a number of events above unity. The electron/muon ν signals and spectra may reflect the neutrino flavour mixing. A surprising τ appearance may occur for a hard ($E_{\nu_\mu} \to E_{\nu_\tau} \geq 4\,\mathrm{GeV}$) flare spectra.

Keywords: Solar and Atmospheric Neutrinos, Neutrino and Gamma Astronomy, Neutrino Physics.

Contents

1. Introduction

The recent peculiar solar flares on October-November 2003 recalls the historical one of February 23th, 1956 [1] and the most powerful event occurred on September 29th, 1989 at 11:30 - 12:00 UT [2, 15]. These events were source of high energetic charged particles with energies: $15\,\mathrm{GeV} \geq E_p \geq 100\,\mathrm{MeV}$; higher energy protons from the sun $E_p \geq 500\,\mathrm{GeV}$ have been also reported (see [10]). A large fraction of these *primary* particles, i.e. solar flare cosmic rays, became a source of both neutrons and *secondary* kaons, $K^{\pm}$, pions, $\pi^{\pm}$ by their particle-particle spallation on the Sun surface first, and then on the Earth's atmosphere [2]. Consequently, $\mu^{\pm}$, muonic and electronic neutrinos and anti-neutrinos, ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$, γ rays, are released by the chain reactions $\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$, $\pi^0 \to 2\gamma$, $\mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$. There are two different sites for these decays to occur, and two corresponding neutrino emissions (see [11]):

1. A brief and sharp solar flare *neutrino burst*, originated within the solar corona;
2. A diluted and delayed terrestrial *neutrino flux*, produced by flare particles hitting the Earth's atmosphere.

The first is a prompt neutrino burst (few seconds/minutes onset) due to charged particles scattering onto the solar shock waves, associated with prompt gamma, X, neutron events. The largest event which occurred at 19:50 UT on November 4 2003 was recorded as an $X28$, the most intense X ray event from our Sun. The consequent *solar* flare neutrinos reached the Earth with a well defined directionality and within a narrow time range. The corresponding average energies $\langle E_{\nu_e} \rangle$, $\langle E_{\nu_\mu} \rangle$ are probably larger compared to an event in the Earth's atmosphere since the associated primary particles ($\pi^{\pm}$, $\mu^{\pm}$) decay in flight at low solar densities, where they suffer negligible energy loss: $\langle E_{\nu_e} \rangle \simeq 50\,\mathrm{MeV}$, $\langle E_{\nu_\mu} \rangle \simeq 100 \div 200\,\mathrm{MeV}$.

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The delayed *neutrino flux* originated in the Earth's atmosphere is due to the arrival of prompt solar charged particles nearly ten minutes later than onset of the radio-X emission. These particles must not be confused with those at lower energy originated in more delayed solar winds. Such nearly relativistic (100–1000 MeV) solar flare cosmic rays are charged and bent by inter-planetary particles and fields. Therefore their arrival and the corresponding neutrino production in the Earth's atmosphere occurs few tens of minutes or even few hours later than the solar X-radio sharp event. As a result, their signal is widely spread and diluted in time. The atmospheric neutrino directions at sea level, following the cosmic rays arrival maps, are nearly isotropic or, more precisely they are slightly clustered near the terrestrial magnetic poles. A large fraction of the energy of the primary solar flare cosmic rays (such as protons and alpha particles) is dissipated by ionization in the earth's atmosphere. Therefore *terrestrial* electronic neutrinos ν_e, $\bar{\nu}_e$, are originated by muons almost at rest because of the dense terrestrial atmosphere, and are leading to a soft terrestrial neutrino flare spectra. Their mean energy $E_{\nu\oplus}$ is on average smaller than the original *solar flare* ones, $\langle E_{\nu\odot}\rangle \simeq 100\,\mathrm{MeV}$, and their total energy ratio $\frac{E_{\nu\oplus}}{E_{\nu\odot}} \leq 10^{-1}$, is also low. Because of the quadratic or linear increase of the cross section with energy, the detection of the terrestrial neutrino flux is harder than the solar one. Moreover, the terrestrial diluted neutrino flux may be hidden (excluding few cases in present detectors) by the comparable steady atmospheric neutrino background. For these reasons we may neglect the low energetic terrestrial *neutrino flux*, even if it is a well defined source of secondary neutrinos. It will be hard to observe this signal with the present statistics of the Super-Kaimokande (SK) detector, but it might be observable in the future larger underground detectors.

In this paper we analyse the observable consequences due to the first prompt solar flare: *a solar neutrino burst*. We consider two mechanisms to produce neutrinos from proton-proton scattering: these flare particles may scatter either outward or inward the solar surface while pointing at the same time to the (Earth) observer. Because of the very different consequent target solar atmosphere, the $\pi^{\pm}$, $\mu^{\pm}$, and ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$ production is different. Our estimate of the solar flare *neutrino burst* is scaled by an integrated flare energy E_{FL}, which is assumed to be of the order of $E_{FL} \simeq 10^{31} \div 10^{32}\,\mathrm{erg}$, by comparison with the known largest solar flare events as those in 1956 and 1989. The recent solar flare spectra are unknown but their energies are extending well above the few GeV threshold necessary to the pion production. To give a rough idea of the order of magnitude of a solar neutrino flare on the Earth, we may compare the *total* flare energy flux Φ_{FL}, at the Sun-Earth distance $d_\odot$ with the corresponding energy flux of the well studied supernovæ explosion SN1987A, occurred on the 23rd February 1987 at a distance d_{SN}:

$$\frac{\Phi_{FL}}{\Phi_{SN}} \simeq \frac{E_{FL}}{E_{SN}}\left(\frac{d_{SN}}{d_\odot}\right)^2 \simeq \frac{1}{30}\left(\frac{E_{FL}}{10^{32}\,\mathrm{erg}}\right)\left(\frac{E_{SN}}{3\cdot 10^{53}\,\mathrm{erg}}\right)^{-1}. \tag{1.1}$$

The ratio, even if smaller than unity, remarks the flare energy relevance. The SN neutrino fluence is probed both experimentally and theoretically while the conversion of the solar flare energy (10^{32} erg) in neutrinos has to be probed yet. However even in a more conservative scenario, where only a fraction $\eta < 0.1$ of the flare energy is converted into neutrinos, the flare energy flux on the Earth is:

$$\Phi_{FL} = 3.5 \cdot \eta \cdot 10^4 \,\mathrm{erg\,cm^{-2}} \left(\frac{E_{FL}}{10^{32}\,\mathrm{erg}} \right). \tag{1.2}$$

We know that Kamiokande detectors observed 11 neutrino events from the 1987A supernovæ explosion, while SK, because of its larger volume, may observe a signal 22 times as large. Therefore, even if $\eta \sim 10\%$ the signal (~ 0.8) is near unity and it may be reached. Moreover the expected pion-muon neutrino flare mean energy ($E_{\nu FL} \simeq 0.1 - 1\,\mathrm{GeV}$) is much larger than the corresponding one for thermal supernovæ ν: $\langle E_{\nu FL} \rangle \geq kT_{\nu SN} \simeq 10\,\mathrm{MeV}$. The consequent $\nu - N$ cross section increases with the square of the energy, therefore the event number, to a first approximation, is larger (by a factor ten or more) than 10 MeV. Consequently, if a fraction ≥ 0.001 of the total flare energy ($E_{FL} \simeq 10^{32}\,\mathrm{erg}$) was emitted into neutrino relics via the $p \to \pi \to \mu$ chain, their arrival on Earth might be nearly detectable ($\sim 1 \div 5$ events) and it would be much worth checking the Super-Kamiokande records at the corresponding X-radio precursor flare; for instance the X-ray maximum on the 28th October, during the 2nd-4th November (edge), and the 13th November 2003 (hidden) solar flare. Gamma signals are also expected in similar events: there are very limited gamma data (OSSE-EGRET) on solar flares and only a very surprising evidence of hard gamma events [16] on the July 2002 solar flare, where hard X-gamma events have been followed in details by RHESSI gamma detector. The associated gamma energy of the 2002 flare is smaller than our neutrino estimate. It is worth reminding to the reader that the absence of large gamma solar flares have been used to infer a bound on anti-meteorite and anti-matter presence in our solar system and galaxy (see [5]). On the other hand, downward gamma and/or hard X flares while being closely absorbed might play a key role in enhancing neutrino signal over the gamma flare. Therefore we consider the total energy of the flare (both kinetic and X) as the main input to compare and to calibrate our predictions of the neutrino signal.

2. The solar flare energy balance

The energy released during the largest known flares is mainly under the form of interplanetary shock waves $E_{FL} \geq 10^{32}\,\mathrm{erg}$ (see [3]) up to $E_{FL} \leq 10^{33}\,\mathrm{erg}$, (see [16]). A large fraction of energy is found in optical emission $E_{FLop} \simeq 8 \cdot 10^{31}\,\mathrm{erg}$ and in soft and hard X-rays (by electromagnetic or nuclear bremsstrahlung), as well as in energetic cosmic rays ($2 \div 5 \cdot 10^{31}\,\mathrm{erg}$). The flare particles might be pointing towards the Earth or they may be just beyond the solar disk, as in the September 1989 event, located behind the West limb of the Sun (105^o West) and those on the 4th - 6th - 13th November 2003. The 1989 flare was *first* observed at a 8.8 Gigahertz radioburst, (because of the refractive index of solar atmosphere), at 11:20 UT and. Later it reached a higher (visible) peak in the X-rays domain (see [2, 11]). Is there any *hidden* underground flare whose unique trace is in a powerful (unobserved) neutrino burst? Secondary gamma rays due to common neutral pion decay, positron annihilations and neutron capture, have a very small cross section, thus there must be an observable signature on the Sun surface of such a powerful

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hidden flare. Nevertheless observed gamma ray flares, do not favor any extreme $E_{FL} \gg 10^{33}\,\mathrm{erg}$ underground flares(see [15, 16]). It must be kept in mind that the rarest event on February ′56 was not observed at gamma wavelengths, because of the absence of such satellite detectors at the time, while the Sept. 29th 1989 event was not detected in gamma rays because it occurred on the opposite solar side. On the other hand lower powerful solar flares as that of the 4th June 1991 have been studied in all radio-X-gamma energy up to tens MeV energy by the OSSE detector of the CGRO satellite. Therefore there are no direct bounds on a larger *hidden* underground flare. One may suspect that a too large solar flare event in its hidden side should be reflected somehow into an electromagnetic cascade which may influence the continuous solar energy spectrum ($E_{\odot} \simeq 3.84 \cdot 10^{33}\,\mathrm{erg}\ s^{-1}$), even in the observable side. Moreover recent accurate heliosismography might be able to reveal any extreme hidden flare energy. We may therefore restrict our most powerful solar flare energy in the range:

$$10^{33}\,\mathrm{erg} \geq E_{FL} \geq 10^{31}\,\mathrm{erg} \tag{2.1}$$

keeping the lowest value as the flare energy threshold.

2.1 The proton-proton pion production in solar flare: a first approximation

The kaon-pion-muon chain reactions and their consequent neutrino relics spectrum in solar atmosphere may be evaluated in detail if the energetic particle (protons, alpha nuclei, . . .) energy spectra is known, as well as the solar density and magnetic configuration. Indeed magnetic screening may reduce high energy particle scattering in the solar flare regions. Current astrophysical theories are able to explain the observed atmospheric neutrino spectrum on Earth, derived by a primary cosmic rays spectrum with a given power law index. By analogy we may try to predict the solar ν spectrum assuming a given solar flare (p) spectrum and the corona density where the solar protons are ejected.

Our approach, ignoring the exact spectrum for protons in recent solar flare and the detailed magnetic configuration, will force us to consider only averaged values, neglecting the (higher energetic) Kaon production. In order to find the interaction probability for an energetic proton ($E_p \simeq 2\,\mathrm{GeV}$) to scatter inelastically with a target proton at rest in solar atmosphere, we must assume an exponential solar density function following the well known solar density models (reference [6]).

$$n_{\odot} = N_0 e^{\frac{-h}{h_0}}\,; \qquad N_0 = 2.26 \cdot 10^{17}\,\mathrm{cm}^{-3}\,, \qquad h_0 = 1.16 \cdot 10^{7}\,\mathrm{cm} \tag{2.2}$$

where h_0 is the photosphere height where flare occurs.

2.2 Interactions of up-going protons in solar flares

The inelastic proton-proton cross section for energetic particles ($E_p > 2\,\mathrm{GeV}$) is nearly constant: $\sigma_{pp}(E > 2\,\mathrm{GeV}) \simeq 4 \cdot 10^{-26}\,\mathrm{cm}^2$. Therefore the scattering probability P_{up} for an upward (respect to the solar surface) energetic proton p_E, to produce pions (or kaons) via nuclear reactions is:

$$P_{up} = 1 - e^{-\int_{h_0=0}^{\infty} \sigma_{pp} n_{\odot} dh} \simeq 0.1\,. \tag{2.3}$$

A terrestrial Observatory whose line of sight includes the solar flare would observe only 10% (or much less, if, as it is well possible $h_0 > 10^7$cm) of the primordial proton flare number, converted into pions and relic muons, neutrinos and electron-positron pairs. Moreover, because of the kinematics, only a fraction smaller than 1/2 of the energetic proton will be released to pions (or kaons) formation. In the simplest approach, the main source of pion production is $p + p \to \Delta^{++} n \to p\pi^+ n$; $p + p \to \Delta^+ p \begin{smallmatrix} \nearrow p+p+\pi^0 \\ \searrow p+n+\pi^+ \end{smallmatrix}$ at the center of mass of the resonance Δ (whose mass value is $m_\Delta = 1232\,\mathrm{MeV}$). The ratio $R_{\pi p}$ between the pion to the proton energy is:

$$R_{\pi p} = \frac{E_\pi}{E_p} = \frac{{m_\Delta}^2 + {m_\pi}^2 - {m_p}^2}{{m_\Delta}^2 + {m_p}^2 - {m_\pi}^2} = 0.276\,. \tag{2.4}$$

Therefore the total pion flare energy due to upward proton is:

$$E_{\pi_{FL}} = P R_{\pi p} E_{FL} = 2.76 \cdot 10^{-2} E_{FL}\,. \tag{2.5}$$

Because of the isotopic spin, the probability to form a charged pion over a neutral one in the reactions above: $p + p \to p + n + \pi^+$, $p + p \to p + p + \pi^0$, is given by the square of the Clebsh Gordon coefficients:

$$C^2_{\frac{\pi^0}{\pi^+}} \simeq \frac{1}{5}\,. \tag{2.6}$$

This ratio imply a larger (nearly an order of magnitude) neutrino fluence over the gamma one. The ratio of the neutrino and muon energy in pion decay is also a small adimensional fraction $R_{\nu_\mu \mu}$

$$R_{\nu_\mu \mu} = \frac{E_{\nu_\mu}}{E_\mu} = \frac{{m_\pi}^2 - {m_\mu}^2}{{m_\pi}^2 + {m_\mu}^2} = 0.271\,. \tag{2.7}$$

Therefore, at the rest frame of the charged pion one finds the mono-cromatic energies for the neutrino and muon : $E_{\nu_\mu} = 29.8\,\mathrm{MeV}$; $E_\mu = 109.8\,\mathrm{MeV}$. However as a first approximation and as an useful simplification after the needed boost of the secondaries energies one may assume that the total pion π^+ energy is equally distributed, in average, in all its final remnants: ($\bar{\nu}_\mu$, e^+, ν_e, ν_μ), or more in detail:

$$E_{\nu_\mu} \geq E_{\bar{\nu}_\mu} \simeq E_{\nu_e} \simeq \frac{1}{4} E_{\pi^+} \tag{2.8}$$

One might notice that the correct averaged energy (by Michell parameters) for neutrino decay μ^+ at rest are: $E_{\bar{\nu}_\mu} = E_{\nu_e} = \frac{3}{10} m_\mu \simeq \frac{1}{4} m_\pi$.

Similar reactions (at lower probability) may also occur by proton-alfa scattering leading to: $p + n \to \Delta^+ n \to n\pi^+ n$; $p + n \to \Delta^o p \begin{smallmatrix} \nearrow p+p+\pi^- \\ \searrow p+n+\pi^o \end{smallmatrix}$. Here we neglect their additional role due to the flavor mixing and the dominance of previous reactions at soft flare spectra.

Therefore $E_{\nu_\mu} > E_{\nu_e}$: however muon neutrino from pion $\pi^\pm$ decays have a much lower mean energy and the combined result in eq. (2.8) is a good approximation. We must consider also the flavour mixing (in vacuum) that leads to an averaged neutrino energy along its path.

To a first approximation the oscillation will lead to a decrease in the muon component and it will make the electron neutrino component harder. We take into account this flavor mixing by a conversion term $\eta_\mu \simeq 1/2$, re-scaling the final muon neutrino signal and increasing the electron spectra component. Because in π-μ decay the μ neutrinos secondary are twice the electron ones, the anti-electron neutrino flare energy is, from the birth place on Sun up to the flavour mixed states on Earth:

$$E_{\bar{\nu}_e FL} \simeq \frac{E_{\nu_\mu FL}}{2} \simeq 2.6 \cdot 10^{28} \left(\frac{E_{FL}}{10^{31}\,\mathrm{erg}} \right) \mathrm{erg}\,. \tag{2.9}$$

The corresponding neutrino flare energy and number fluxes at sea level are:

$$\Phi_{\bar{\nu}_e FL} \simeq 9.15 \left(\frac{E_{FL}}{10^{31}\,\mathrm{erg}} \right) \mathrm{erg\,cm}^{-2} \tag{2.10}$$

$$N_{\nu_e} \simeq N_{\bar{\nu}_e} \simeq 5.7 \cdot 10^4 \left(\frac{E_{FL}}{10^{31}\,\mathrm{erg}} \right) \left(\frac{\langle E_{\bar{\nu}_e} \rangle}{100\,\mathrm{MeV}} \right)^{-1} \mathrm{cm}^{-2}\,. \tag{2.11}$$

This neutrino number is larger but comparable with a different value calculated elsewhere (reference [7]). The flux energy in eq. (2.10) is nearly 4000 times smaller than the energy flux in eq. (1.2) and, as we shall see, it may be nearly observable by present detectors. This flux at GeV energy may correspond approximately to a quarter of a day atmospheric neutrino integral fluence (for each flavor specie). Therefore in this rough approximation we may expect a signal at the threshold level (nearly half an event). The largest neutron and gamma flare energies should be (and indeed are) comparable or even much larger ($February 1956$) than the upward neutrino flux energy in eq. (2.10). The exceptional solar flare on $Sept. 29th, 1989$ as well as the most recent on 2nd–4th November 2003 took place in the nearly hidden disk side and we may look now for their horizontal or down-ward secondary neutrinos. Their scattering are more effective and lead to a larger pion production. The processes we describe here are analogous to those considered for horizontal and upward neutrino induced air-showers inside the Earth Crust (see [12]) and nearly ultra high horizontal showers (detectable by EUSO). The solar neutrino flare production is enhanced by a higher solar gas density where the flare beam occurs. Moreover a beamed X-flare may suggest a corresponding beamed pion shower whose mild beaming naturally increases the neutrino signal. Most of the downward neutrino signal discussed in the next sections, as well as their pion and muon secondaries, is generated in a mild relativistic regime. Therefore a mild outward neutrino burst may be expected outside the sun surface even when the flare is hitting downward (with a little anisotropy suppression) pointing back towards the Earth.

2.3 Proton interactions for vertical down-going solar flare

High energetic protons flying downward (or horizontally) to the Sun center are crossing larger (and deeper) solar densities and their interaction probability P_d, is larger than the previous one (P_{up}) (see section 2.2). The proton energy losses due to ionization, at the atmospheric solar densities where most of the $p-p$ scattering take place, are low respect to the nuclear ones and most of the proton flare energy is converted into pion-Kaon nuclear productions with few losses.

If the proton direction is tangent to the sun surface or if the protons are travelling downward towards the solar core, the interaction probability is even larger than one. Consequent unstable and short lived pions of few GeV will decay in flight because of repetitive nuclear reactions at those solar atmosphere densities are rare; the pion number density n_π is described by the following equation:

$$\frac{dn_\pi}{dt} = \int\int \left[\frac{d^2 n_{pE}}{dEd\Omega} n_{pT}\sigma_{pp}v_{pE} - \frac{d^2 n_{pE}}{dEd\Omega} n_\pi \sigma_{p\pi} v_\pi - \frac{d^2 n_\pi}{dEd\Omega} n_\pi \sigma_{\pi\pi} v_\pi \right] dEd\Omega - \\ - \int_{m_\pi}^{\infty} \frac{d^2 n_\pi}{dE} \Gamma_\pi \left(\frac{m_\pi}{E_\pi} \right) dE_\pi \, ; \tag{2.12}$$

where n_{pE}, n_{pT}, n_π are the number density of the flare energetic and target protons, $\sigma_{pp}(E)$, $\sigma_{p\pi}(E)$, $\sigma_{\pi\pi}(E)$, are the p-p, p-π, π-π cross sections. The velocities v_{pE}, v_π are near the velocity of light and $\Gamma_\pi = 3.8 \cdot 10^7 s^{-1}$. The last term in eq. (2.12), due to the relativistic pion decay, at solar densities as in eq. (2.2) and at an energy $E_\pi \simeq \mathrm{GeV}$, is nearly six order of magnitude larger than all other terms, therefore the pion number density n_π should never exceed the corresponding proton number density n_{pE}. However the integral number of all pion stable relics ($\bar{\nu}_\mu$, ν_μ, ν_e, $\bar{\nu}_e$, e^-) may exceed, in principle, the corresponding number of proton flare, because each proton may be a source of more than one pion chain. The proton number density below the photosphere ($h < 0$) is described by a polytropic solution, but it may also be approximated by a natural extrapolation of the eq. (2.2) with a negative height h. It is easy to show that the interaction probability for a relativistic proton ($E_{pE} \gg \mathrm{GeV}$) reaches unity at depth $h = -278$ Km which is the interaction length. At the corresponding density ($n\odot \sim 2.2 \cdot 10^{18} \mathrm{cm}^{-3}$) the proton ionization losses, between any pair of nuclear reactions are negligible (few percent). Unstable relic pions decay (almost) freely after a length $L_\pi \simeq (E_\pi/m_\pi){\Gamma_\pi}^{-1}c \simeq 7.8 \cdot 10^2 (E_\pi/m_\pi)\mathrm{cm}$. The secondary muons μ do not loose much of their energy ($\leq 1\%$) in ionization, ($E_\mu \leq 0.1 - 1\,\mathrm{GeV}$) during their nearly free decay: the muon flight distance is $L_\mu = \frac{E_\mu}{m_\mu}{\Gamma_\mu}^{-1}c = 6.58 \cdot 10^4 (E_\mu/m_\mu)\mathrm{cm}$, and the ionization losses are: $dE_\pi/dx \simeq dE_\mu/dx \simeq 10^{-5}\,\mathrm{MeV\,cm}^{-1}$. In conclusion most of the solar flare energy will contribute to downward muon energy with an efficiency η near unity. At deeper regions, near $h < -700$ Km where the solar density is $n_\odot \geq 10^{20}\ \mathrm{cm}^{-3}$, a GeV-muon will dissipate most of its energy in ionization before decaying. In that case the energy ratio between muon relics and primary protons is much smaller than unity. Only a small fraction of protons will reach by a random walk such deeper regions and we may conclude that, in general, the flare energy relations are:

$$E_{\pi FL} \equiv \eta E_{FL} \leq E_{FL} \\ E_{\bar{\nu}_e FL} \simeq \frac{E_{\nu_\mu FL}}{2} \simeq 9.4 \cdot 10^{30} \eta \left(\frac{E_{FL}}{10^{32}\,\mathrm{erg}} \right) \mathrm{erg}\,. \tag{2.13}$$

This result is nearly 36 times larger than the corresponding one for *up-ward* neutrinos in eq. (2.8). Terrestrial neutrino relics from cosmic rays produced by pion chain reactions, lead to a predicted and observed asymmetry (see [8]) between $\bar{\nu}_e$, ν_e, due to the positive proton charge predominance both in target and incident beam:

$$\frac{N_{\nu_e}}{N_{\bar{\nu}_e}} = \frac{N_{\mu^+}}{N_{\mu^-}} \simeq 1.2$$

at energies $10\,\mathrm{GeV} > E_\nu > 100\,\mathrm{MeV}$. (Note that in a total absence of π^- production the above ratio may reach a factor 2). Therefore the energy component of the observable flare should be marginally reduced in eq. (2.13), even assuming a low flare output (10^{31} erg):

$$E_{\bar{\nu}_e} \simeq 7.8 \cdot 10^{-2} \eta E_{FL} = 7.8 \cdot 10^{29} \eta \left(\frac{E_{FL}}{10^{31}\,\mathrm{erg}} \right) \mathrm{erg}\,. \tag{2.14}$$

3. Solar neutrino flare events in SK-II

We cannot say much about the solar flare neutrino spectrum because of our ignorance on the recent primordial proton flare spectra. The solar flare are usually very soft. We may expect a power spectrum with an exponent equal or larger than the cosmic ray proton spectrum. Therefore we consider here only averaged neutrino energy $\langle E_\nu \rangle$ at lowest energies (below near GeV) and we scale the result above, eq. (2.14), for the anti-neutrino numbers at sea level:

$$\langle N_{\bar{\nu}_e} \rangle \simeq 1.72 \cdot 10^6 \eta \left(\frac{\langle E_{\bar{\nu}_e} \rangle}{100\,\mathrm{MeV}} \right)^{-1} \left(\frac{E_{FL}}{10^{31}\,\mathrm{erg}} \right) \mathrm{cm}^{-2} \tag{3.1}$$

$$\langle N_{\bar{\nu}_\mu} \rangle \simeq 4.12 \cdot 10^6 \eta \left(\frac{\langle E_{\bar{\nu}_\mu} \rangle}{100\,\mathrm{MeV}} \right)^{-1} \left(\frac{E_{FL}}{10^{31}\,\mathrm{erg}} \right) \mathrm{cm}^{-2}\,. \tag{3.2}$$

We now consider the neutrino events due to these number fluxes at Super-Kamiokande II; other detectors as SNO (and AMANDA if the spectra was extremely hard) might also record a few events but at much lower rate. The observable neutrino events, due to inverse beta decay ($\bar{\nu}_e + p \to n + e^+$; $\bar{\nu}_\mu + p \to \mu^+ + n$), at Super-Kamiokande detectors are:

$$N_{ev} = \sum_i \int \frac{dN_{\bar{\nu}_i}}{dE_i} \sigma_{\bar{\nu}_i p}(E_{\nu_i}) N_{p_{SK}} dE_i \tag{3.3}$$

$i = e, \mu$. A comparable neutrino events, due to stimulated beta decay ($\nu_e + n \to p + e^-$; $\nu_\mu + n \to \mu^- + p$), must also take place (see an updated reference [17]). We may approximate this number with an averaged one due to an effective neutrino energy $\bar{E}_\nu$:

$$N_{ev} = \sum_i \langle N_{\bar{\nu}_i} \rangle \sigma_{\bar{\nu}_i p}(\bar{E}_{\nu_i}) N_{p_{SK}}\,. \tag{3.4}$$

Where $N_{p_{SK}}$ is the proton number in the Super-Kamiokande detector $N_{p_{SK}} = \frac{N_p}{N_{H_2O}} N_{\mathrm{nucl}}$; $N_{\mathrm{nucl}} = 22KT \cdot N_A = 3.33 \cdot 10^{34}$; $N_p/N_{H_2O} = 8/18$; $N_{p_{SK}} = 7.38 \cdot 10^{33}$. The cross section is an elaborated analytical formula (see Strumia et all. 2003 [14]). This expression, in agreement with a full detailed result within few thousandths for $E_\nu \leq 300\,\mathrm{MeV}$, is

$$\sigma(\bar{\nu}_e p) \approx 10^{-43}\,\mathrm{cm}^2\, p_e E_e\, E_\nu^{-0.07056 + 0.02018 \ln E_\nu - 0.001953 \ln^3 E_\nu}\,, \qquad E_e = E_\nu - \Delta\,. \tag{3.5}$$

Where $\Delta = m_n - m_p$; E_e is the energy of the escaping electron. In a simpler low-energy approximation (see Bemporad et all., 2002 e.g. [13])

$$\sigma \approx 9.52 \times 10^{-44} \frac{p_e E_e}{\mathrm{MeV}^2}\,\mathrm{cm}^2, \qquad E_e = E_\nu \pm \Delta \text{ for } \bar{\nu}_e \text{ and } \nu_e, \tag{3.6}$$

In a more direct form (see [11]), at low energy ($10\,\mathrm{MeV} \leq E_{\bar{\nu}_e} \leq \mathrm{GeV}$)

$$\sigma_{\bar{\nu}_e p} \simeq 7.5 \cdot 10^{-44} \left(\frac{E_{\bar{\nu}_e}}{\mathrm{MeV}}\right)^2 \mathrm{cm}^2\,. \tag{3.7}$$

The expected neutrino event, during the flare may increase twofold as we mentioned above because of both a solar burst and a later diluted terrestrial flux; for the terrestrial neutrino flux (during the recent $28/29 Oct.2003$ flare) due to solar protons hitting the atmosphere we expect at least:

$$N_{ev} \cong 1.7 \cdot 10^6 \cdot 7.38 \cdot 10^{33} \cdot 6 \cdot 10^{-40} \simeq 7.5 \cdot \eta \left(\frac{E_{FL}}{10^{31}\,\mathrm{erg}}\right). \tag{3.8}$$

These events in the *terrestrial flux* should almost double the common atmospheric neutrino flux background (5.8 event a day). For the prompt neutrino solar burst in the Sun we expect (if occurred in the hidden or horizontal solar disk) a similar number in a very narrow time window. Naturally this result might be too optimistic. In order to obtain a more severe result we now tune our expectation with the event number due to the well known supernovæ SN1987A where we know (or we hope to know) the primordial neutrino energy: $\sum E_{\nu_{SN}} \simeq 3 \cdot 10^{53}$ erg and $\bar{E}_{\bar{\nu}_e} \simeq 10\,\mathrm{MeV}$. We know (by cosmology and Z_0 width decay in LEP) that the possible neutrino flavours states are $N_F = 6$ (ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$). The Earth-SN1987A distance $d_{SN} = 1.5 \cdot 10^{23}$cm leads to:

$$N_{ev\bar{\nu}_e} = \frac{N_{\nu_{SN}}}{N_F} \sigma_{\bar{\nu}_e p}(\bar{E}_{\nu_{SN}}) N_{pSK} = 11 \left(\frac{E_{SN}}{3 \cdot 10^{53}\,\mathrm{erg}}\right)\left(\frac{\bar{E}_\nu}{10\,\mathrm{MeV}}\right). \tag{3.9}$$

It should be noted that the quadratic energy $\bar{E}_\nu$ dependence of the cross section $\sigma_{\bar{\nu}_e p}$ (see eq. (3.7)) and the inverse energy $\bar{E}_\nu$ relation of the neutrino flux number leads to the linear dependence in eq. (3.9). However, the inverse beta decay processes increases quadratically with energy $\bar{E}_\nu$ up to a value smaller than $m_p \sim \mathrm{GeV}$, above which the cross section in eq. (3.4) grows linearly with the energy: $\bar{\nu}_e + p \to e^+ + n$; $\bar{\nu}_\mu + p \to \mu^+ + n$; $\nu_e + n \to e^- + p$; $\nu_\mu + n \to \mu^- + n$;

$$\sigma_{\bar{\nu}_e p} \simeq 6.2 \cdot 10^{-39}\,\mathrm{cm}^2 \left(\frac{\bar{E}_{\bar{\nu}_e}}{\mathrm{GeV}}\right); \qquad \sigma_{\nu_e n} \simeq 3.5 \cdot 10^{-39}\,\mathrm{cm}^2 \left(\frac{\bar{E}_{\nu_e}}{\mathrm{GeV}}\right) \mathrm{cm}^2\,. \tag{3.10}$$

The formulas above are approximations only within an energy window $E_{\nu_\mu}, E_{\bar{\nu}_\mu}, E_{\nu_e}, E_{\bar{\nu}_e} \simeq 100 - 1000\,\mathrm{MeV}$. As we shall see, we may neglect the prompt neutrino-electron scattering processes due to charged or neutral current cross sections:

$$\begin{aligned} \sigma_{\nu_e e} &\simeq 9 \cdot 10^{-45} \left(\frac{\bar{E}_\nu}{\mathrm{MeV}}\right) \mathrm{cm}^2\,; \qquad & \sigma_{\nu_\mu e} &\simeq 1.45 \cdot 10^{-45} \left(\frac{\bar{E}_\nu}{\mathrm{MeV}}\right) \mathrm{cm}^2 \\ \sigma_{\bar{\nu}_e e} &\simeq 3.7 \cdot 10^{-45} \left(\frac{\bar{E}_\nu}{\mathrm{MeV}}\right) \mathrm{cm}^2\,; \qquad & \sigma_{\bar{\nu}_\mu e} &\simeq 1.24 \cdot 10^{-45} \left(\frac{\bar{E}_\nu}{\mathrm{MeV}}\right) \mathrm{cm}^2\,. \end{aligned} \tag{3.11}$$

Indeed these values are nearly 100 times smaller (at $\bar{E}_\nu \sim 100\,\mathrm{MeV}$) than the corresponding nuclear ones in eq. (3.7) and eq. (3.10). We consider the neutrino flare signals at Super-Kamiokande due to either $\bar{\nu}_e + p \to n + e^+$ and $\bar{\nu}_\mu + p \to \mu^+ + n$, $\nu_e + n \to e^- + p$; $\nu_\mu + n \to \mu^- + n$; keeping in mind, for the latter, the threshold energy E_{ν_μ},$E_{\bar{\nu}_\mu} > 113\,\mathrm{MeV}$. We may summarize from eq. (3.1) the expectation event numbers at Super-Kamiokande as follows: $N_{ev\bar{\nu}_e} \simeq 0.63\eta(\bar{E}_{\bar{\nu}_e}/35\,\mathrm{MeV})(E_{FL}/10^{31}\,\mathrm{erg})$; $\bar{E}_{\bar{\nu}_e} \leq 100\,\mathrm{MeV}$; $N_{ev\bar{\nu}_e} \simeq 1.58\eta(E_{FL}/10^{31}\,\mathrm{erg})$; $\bar{E}_{\bar{\nu}_e} \geq 100 - 1000\,\mathrm{MeV}$; $N_{ev\bar{\nu}_\mu} \simeq 3.58\eta(E_{FL}/10^{31}\,\mathrm{erg})$; $\bar{E}_{\bar{\nu}_\mu} \geq 200 - 1000\,\mathrm{MeV}$; where $\eta \leq 1$. The neutrino events in Super-Kamiokande may be also recorded as stimulated beta decay on oxygen nuclei. Indeed such reactions exhibit two possible channels: $\nu_e + O \to F + e^-$, $\bar{\nu}_e + O \to N + e^+$; they have been analyzed by W. C. Haxton 1987 [9]). For this reason our preliminary estimate is just a lower bound for any high energetic ($E_{\nu_e} > 100\,\mathrm{MeV}$) neutrino spectrum.

3.1 The surprising role of solar neutrino flavor mixing: the τ appearence

The Earth-Sun distance $D_{\oplus\odot}$ is large enough to guarantee a complete flavor mixing even for hundred MeV or GeV neutrino energies. Indeed the oscillation distance in vacuum is $L_{\nu_\mu - \nu_\tau} = 2.48 \cdot 10^9\,\mathrm{cm}(E_\nu/10^9\,eV)(\Delta m_{ij}^2/(10^{-2}\,\mathrm{eV})^2)^{-1} \ll D_{\oplus\odot} = 1.5 \cdot 10^{13}\,\mathrm{cm}$. The consequent flavor mixing will increase the average energy of the anti neutrino electron component respect to the one at its birth. This will also increase the neutrino electron component while it will reduce the corresponding muon component leading to:

$\eta_\mu/\eta_e \simeq 1/2$ and to $N_{ev\bar{\nu}_\mu} \simeq N_{ev\bar{\nu}_e} \simeq 2(\langle E_{\nu_\mu}\rangle/200\,\mathrm{MeV})(\langle E_{FL}\rangle/10^{31}\,\mathrm{erg})$; $N_{ev\nu_\mu} \simeq N_{ev\nu_e}$ as well as a comparable, ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ energy fluence and spectra. At energies above the τ threshold energy $E_{\nu_\mu} \geq 3.46\,\mathrm{GeV}$ a surprising τ appearance may occur: this requires a hard ($E_{\nu_\mu} \to E_{\nu_\tau} \simeq 4\,\mathrm{GeV}$) flare spectra.

Any positive evidence for such events will mark a new road to Neutrino Astrophysics, to be complementary to lower neutrino energy from Sun and Supernovæ. New larger generations of neutrino detectors will be more sensitive to such less powerful, but more frequent and energetic solar flares, than to the rarest extragalactic supernovæ events (as the one from Andromeda).

4. Conclusions

The recent solar flare occurred on October-November 2003, as large as the September $29th, 1989$ one, might be an exceptional source of cosmic, gamma, neutron rays and neutrinos. Their minimum event number at Super-Kamiokande $N_{ev\bar{\nu}_\mu} \simeq N_{ev\bar{\nu}_e} \simeq 2(\langle E_{\nu_\mu}\rangle/200\,\mathrm{MeV})(\langle E_{FL}\rangle/10^{31}\,\mathrm{erg})$; $N_{ev\nu_\mu} \simeq N_{ev\nu_e}$ is near or above unity. The background due to energetic atmospheric neutrinos at the Japanese detector is nearly 5.8 event a day corresponding to a rate $\Gamma \simeq 6.710^{-5} s^{-1}$. The lowest and highest predicted event numbers $(1 \div 5)$ η, $(\eta \leq 1)$ within the narrow time range defined by the sharp X burst $(100s)$, are above the background. Indeed the probability to find by chance one neutrino event within a $1-2$ minute $\Delta t \simeq 10^2 s$ in that interval is $P \simeq \Gamma \cdot \Delta T \simeq 6.7 \cdot 10^{-3}$. For a Poisson distribution the probability to find $n = 1, 2, 3, 4, 5$ events in a narrow time window might reach extremely small values: $P_n \cong e^{-P} \cdot \frac{P^n}{n!} \simeq \frac{P^n}{n!} = (6.7 \cdot 10^{-3}, 2.25 \cdot 10^{-5}, 5 \cdot 10^{-8}, 8.3910^{-11}, 1.1 \cdot 10^{-13})$.

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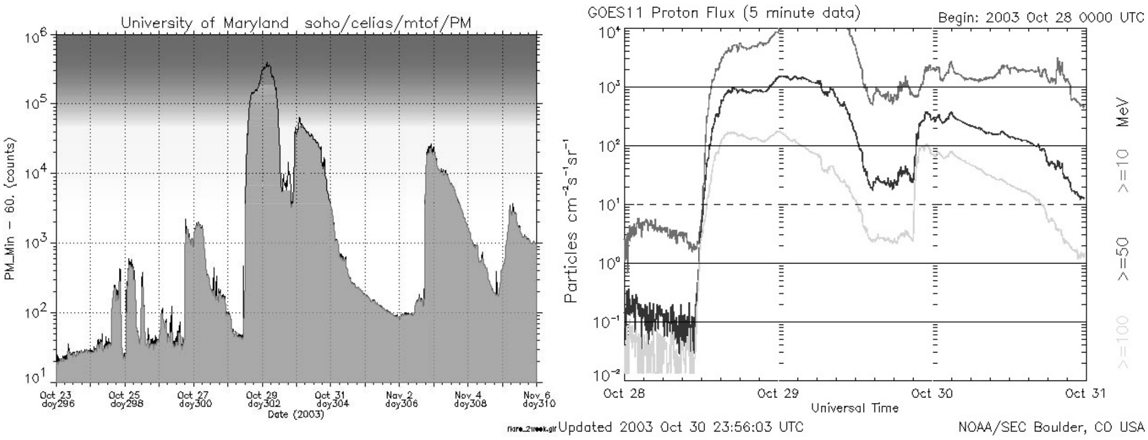

Figure 1: Proton solar flare flux (left: all the events during 23 October-6 November 2003 at lowest energies); (right: detail of part (10-100 Mev) energy the spectra); the data are respectively from SOHO and GOES11 satellite experiments.

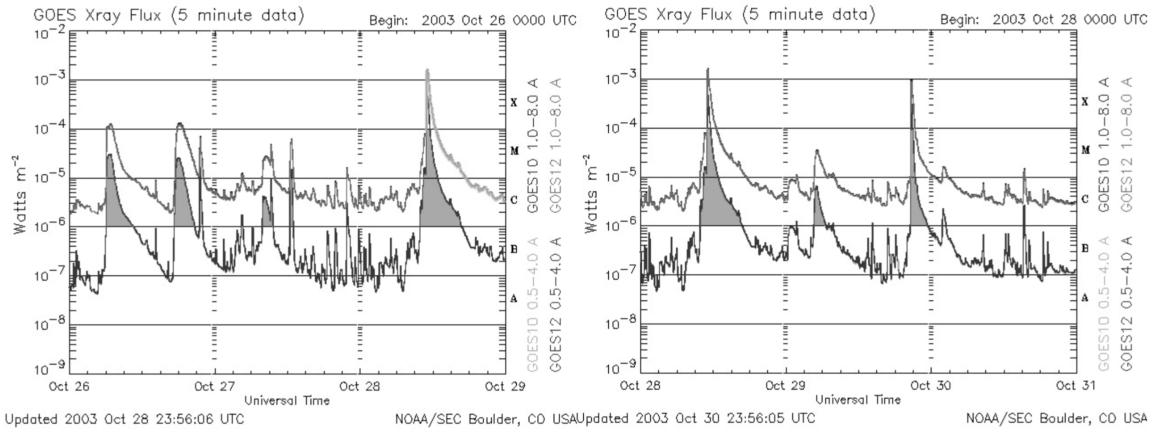

Figure 2: X Solar Flare on-set on 26-29th October 2003 by GOES satellite: readable are the X-peak outburst.

Therefore the possible presence of one or more high energetic (tens-hundred MeVs) positrons (or better positive muons) as well as negative electrons or muons, in Super-Kamiokande at X-flare onset time, may be a well defined signature of the solar neutrino flare. A surprising discover of the complete mixing from the τ appearance may occur for hard ($E_{\nu_\mu} \to E_{\nu_\tau} > 4\,\mathrm{GeV}$) flare spectra. A steep proton flare spectrum, where a large flare energy fraction is at a low proton energies may reduce σ_{pp} inelastic cross-sections and increase the elastic ones, reducing the pion-neutrino creations. At low flare energy $E_{FL} < 10^{32}$ erg, any neutrino muon spectra where $\bar{E}_{\bar{\nu}_\mu} < 100\,\mathrm{MeV}$, or any proton-magnetic field interaction may suppress our estimates. Therefore our considerations are only preliminary and they must be taken cautiously (given the delicate chain of assumptions and simplifications). We hope to stimulate with our work related research in gamma/optical wavelengths, in the study of the neutron component of cosmic rays, and in neutrino underground detectors to investigate the solar activity. In particular we suggest to control

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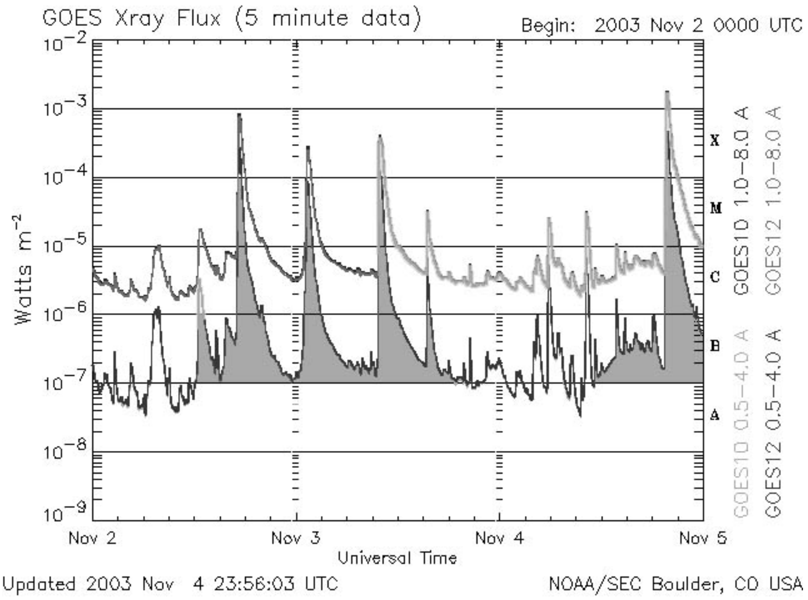

Figure 3: X Solar Flare on-set 2nd-4th November 2003 by GOES satellite: readable are the X-peak outburst.

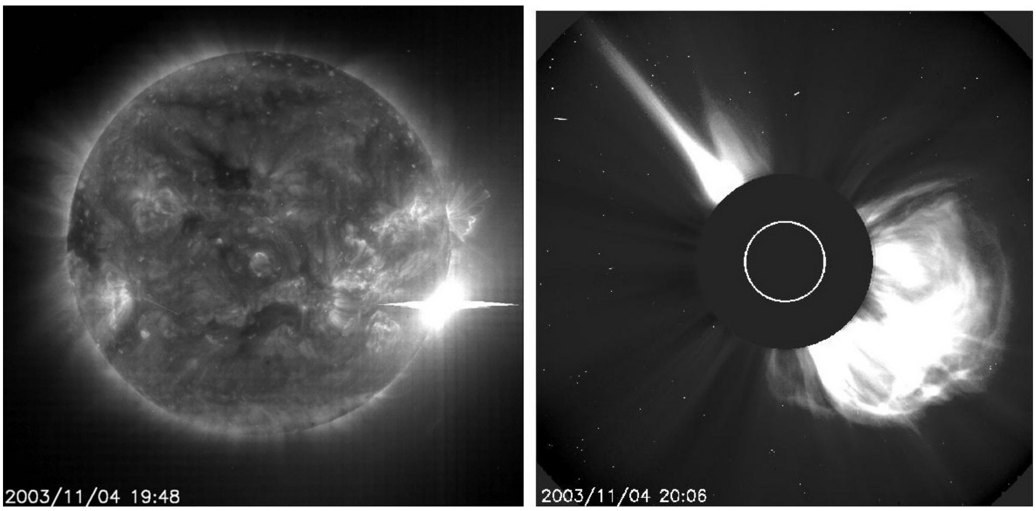

Figure 4: X Solar Flare on 4th November 2003 observed by GOES and SOHO satellites: note the sharp outburst at 19:48-20:08 UT.

the very Super-Kamiokande data records on $October - November$ solar flare X-radio peak activity, namely on $26 - 28 - 30$th October and 2nd–4th and 13 November X-ray onset (see figures below for time details). We like to point the attention to the hard X onset at $19 : 48$ U.T. on 4th November 2003. Finally we notice that the new larger neutrino detectors such as UNO might be at the same time ideal laboratories for solar neutrino flare and flavour mixing, as well as the most rapid alert system monitoring coronal mass ejection, very dangerous for orbiting satellites.

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