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Very high-energy neutrinos from the Sun

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Abstract. We argue here that the Sun is a bright point source of very high-energy (VHE) neutrinos, which are produced by the interactions of cosmic rays with solar matter. The estimated flux of ν_μ and $\bar{\nu}_\mu$ from the Sun exceeds considerably the atmospheric neutrino background at an energy above ~1 TeV. The flux of the VHE solar neutrino should be used as a 'standard candle' of neutrino astronomy of point sources for a future generation of neutrino telescopes.

1. Introduction

Neutrino astronomy is an actively developing branch of high-energy astrophysics and particle physics. Neutrinos are the decay products of pions and kaons and, therefore, they are tracers of the most energetic processes in the Universe. Neutrinos are not subject to magnetic deflection in space and reveal the direction of location of their origin. Since neutrinos are weakly interacting particles, they are able to travel through a large amount of matter without absorption. Neutrinos can provide very fruitful information on various stages of stellar evolution and they enable us to view inner regions of stars and other dense objects which are not visible by electromagnetic radiation. The high-energy neutrinos play also a key role in the study of the origin of high-energy cosmic rays. Therefore, experiments with neutrino telescopes are important for neutrino astronomy and cosmic ray physics, and also for cosmology and elementary particle physics.

High-energy neutrino fluxes from astrophysical sources have been discussed actively from the end of 1970's in connection with proposals to build large neutrino experiments. It is usually supposed that the most powerful sources of high-energy neutrinos are: supernovae, active galactic nuclei, the Galactic Centre, energetic γ-ray and cosmic ray sources etc. The estimations of the neutrino fluxes are based on the 'scaling' of the neutrino flux from the observed γ-ray flux, but the physical conditions in objects (density of matter, particle flux, spectrum etc) are not known accurately. This is the reason why the estimations of neutrino fluxes have large uncertainties. Until now the VHE neutrino flux has not been detected from any extraterrestrial objects.

The Sun also can be an effective source of VHE neutrinos, which are produced via interactions of VHE cosmic rays with solar matter (Moskalenko *et al* 1991, Seckel *et al* 1991). Since the VHE cosmic ray flux near the Earth is well known, the neutrino flux can be calculated accurately.

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Here we present the detailed calculations of the VHE solar neutrino ($\nu_\mu + \bar{\nu}_\mu$) flux, originating from the decay of pions and kaons arising from the interaction of VHE cosmic rays with rare gases of the Sun's atmosphere.

The new generation of large neutrino detectors (such as, for example, DUMAND, AMANDA, GRANDE, SINGAO) are briefly discussed.

2. Cosmic neutrinos

High-energy neutrinos ($E > 50$–100 GeV) are generated in cosmic objects as a result of interactions of accelerated particles (cosmic rays) with atomic nuclei or with low-energy photons. The basic schemes for generation of VHE neutrinos are decays of the unstable secondaries (mainly charged pions) produced in pp interactions:

$$\begin{aligned} & \mathrm{p} + \mathrm{p} \rightarrow \pi^{\pm}(\mathrm{K}^{\pm}) + \text{anything} \\ & \qquad\qquad \hookrightarrow \mu^{\pm} + \nu_\mu \\ & \qquad\qquad\quad \hookrightarrow \mathrm{e}^{\pm} + \nu_\mu + \nu_\mathrm{e}. \end{aligned} \tag{1}$$

For detection of cosmic neutrinos the reaction of muon production ($\nu_\mu + \mathrm{N} \rightarrow \mu + \text{anything}$) in a detector environment is used. The direction of a source of neutrinos is determined from trajectories of produced muons, which are, at an energy $\geqslant 100$ GeV, practically the same as those of the primary neutrinos.

The discrimination of the neutrino energy is a complex problem, because: (i) the muon production by VHE neutrinos is located, in general, outside the detector; (ii) the muon does not carry away all the neutrino energy. Therefore, the measurement of the muon energy would only give a lower limit of the parent neutrino energy. This is further complicated since the energy losses of muons have large fluctuations.

These effects limit the energy resolution of any detector. At energies greater than about 1 TeV, however, the cross section of the muon pair production increases rapidly with energy, which presents an opportunity for some energy discrimination. That is why the threshold energy of neutrino astronomy of local sources is at about 1 TeV.

Since the end of the 1970's, high-energy neutrino fluxes from a number of astrophysical objects have been calculated in connection with proposals for building the DUMAND telescope (e.g. Berezinskii *et al* 1990). The most powerful sources, as supposed, are: supernovae, active galactic nuclei, the Galactic Centre, galactic sources of γ-rays (e.g. Cygnus X-3), cosmic ray sources, and so on. Such estimations of neutrino fluxes are based on the 'scaling' of the neutrino flux from the observed γ-ray flux, but the physical conditions in objects (density of matter, particle flux, spectrum etc) are not known accurately; thus, the estimations of neutrino fluxes have large uncertainties.

In figure 1 the selections of predicted neutrino fluxes from point sources (figure 1(a)) and diffuse fluxes (figure 1(b)) are shown (Barwick *et al* 1992). It is seen that the fluxes reach atmospheric neutrino flux at energies $\sim 10^{14}$–10^{15} eV, so these fluxes can be measured in principle at an energy greater than $\sim 10^{14}$ eV.

At present a new generation of neutrino detectors are being actively discussed: the deep underwater/ice and the surface type. The greatest neutrino detector projects are: DUMAND, AMANDA, GRANDE, SINGAO etc (e.g. see Barwick *et al* 1992,

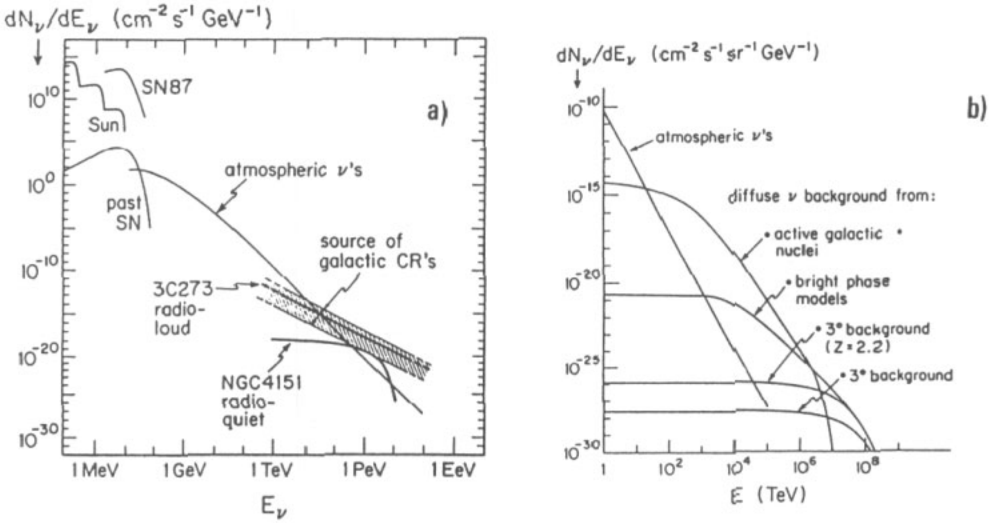

Figure 1. A selection of predicted $\nu_\mu + \bar{\nu}_\mu$ neutrino fluxes from point sources (a) and diffuse fluxes (b). They are compared to the atmospheric neutrino flux (Barwick *et al* 1992). Sources include active galactic nuclei, neutrinos produced by extra-galactic cosmic rays interacting with 2.7 K background photons etc. The atmospheric neutrino background (a) is shown for 2π str upcoming muons.

Sobel 1991). DUMAND—Deep Underwater Muon And Neutrino Detector—consists of a water Cerenkov array (area ~20 000 m^2) to be deployed in the Pacific ocean near the island of Hawaii; AMANDA—Antarctic Muon And Neutrino Detector Array—is similar to that of DUMAND, but located in the polar ice cap (area ~20 000 m^2); GRANDE—Gamma Ray And Neutrino Detector—is a large-area (~30 000 m^2) water Cerenkov detector, and it is proposed to locate it in a water-filled excavation; SINGAO—Southeren Italy Neutrino and Gamma Astronomy Observatory—should comprise several planes of resistive-plate chambers (area ~15 000 m^2). However, they are still too small to allow the detection of VHE neutrino flux from point sources. A further generation of neutrino detectors with an area of about 10^5 m^2 is required.

3. Solar neutrinos of very high energy

In our short letter (Moskalenko *et al* 1991) we have drawn attention to the Sun as an effective VHE neutrino source. Here we calculate in detail the VHE solar neutrino ($\nu_\mu + \bar{\nu}_\mu$) flux, which appears because of the decay of unstable secondaries (charged pions and kaons) produced in collisions of high-energy cosmic particles with rare gases of the solar corona (as is drawn in figure 2). Since the VHE cosmic ray flux near the Earth is well known, the neutrino flux can be calculated accurately.

The neutrino production spectrum by protons of power-law energy spectrum has been calculated (Berezinskii *et al* 1990):

$$F_\nu(>E) = \varphi_\gamma n_{\mathrm{H}} \sigma_{\mathrm{pp}}(E/f) k E^{-\gamma} \, (\mathrm{cm}^{-3}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}) \qquad (2)$$

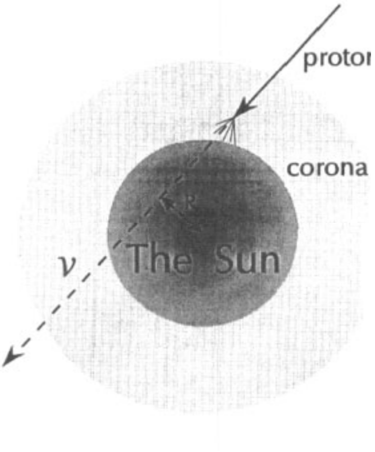

Figure 2. A schematic diagram of the neutrino production by VHE cosmic ray interactions with rare gas of the solar corona.

where E is the neutrino energy, φ_ν is the neutrino yield function, n_{H} is the number density of the gas, $\sigma_{\mathrm{pp}}(E/f)$ is the proton–proton inelastic cross section, f is the part of the proton energy that the neutrino takes away, and $kE^{-\gamma}$ is the integral flux of cosmic rays. Formula (2) is valid for the low-density gas, such that all mesons produced in pp collisions decay before they have time to interact.

For a thick layer of matter, when protons lose all their energy, the neutrino intensity is:

$$I_\nu(>E) = \frac{\varphi_\nu k E^{-\gamma}}{(1-\alpha^\gamma)} \, (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}) \tag{3}$$

where α is the inelasticity coefficient of pp interactions ($\alpha \approx 0.5$). The VHE neutrino flux near the Earth from the Sun is:

$$I_0(>E) = \pi I_\nu(>E) R_\odot^2 / D^2 \, (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}) \tag{4}$$

where $R_\odot$ is the solar radius, D is the distance from the Sun, and $\pi I_\nu(>E)$ is the neutrino flux near the solar surface. Underground neutrino flux from the cosmic ray interactions in the Earth's atmosphere (background) within the solid angle which covers the Sun is:

$$I_{\mathrm{b}}(>E) = \pi \sin^2(0.25^\circ) I_\nu(>E) \, (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}) \tag{5}$$

therefore we obtain the estimation:

$$I_0(>E)/I_{\mathrm{b}}(>E) = 1 \tag{6}$$

for the Sun at all energies, as $R_\odot/(D \sin 0.25^\circ) = 1$.

Actually, two effects change this estimation. The first one is the steepening of the atmospheric neutrino flux at energies above ~200 GeV (e.g. Allkofer *et al* 1978, Stecker 1979, Volkova 1990), due to the VHE $\pi^\pm$-mesons (produced during EAS development) having time to interact before the decay. For the solar neutrinos this

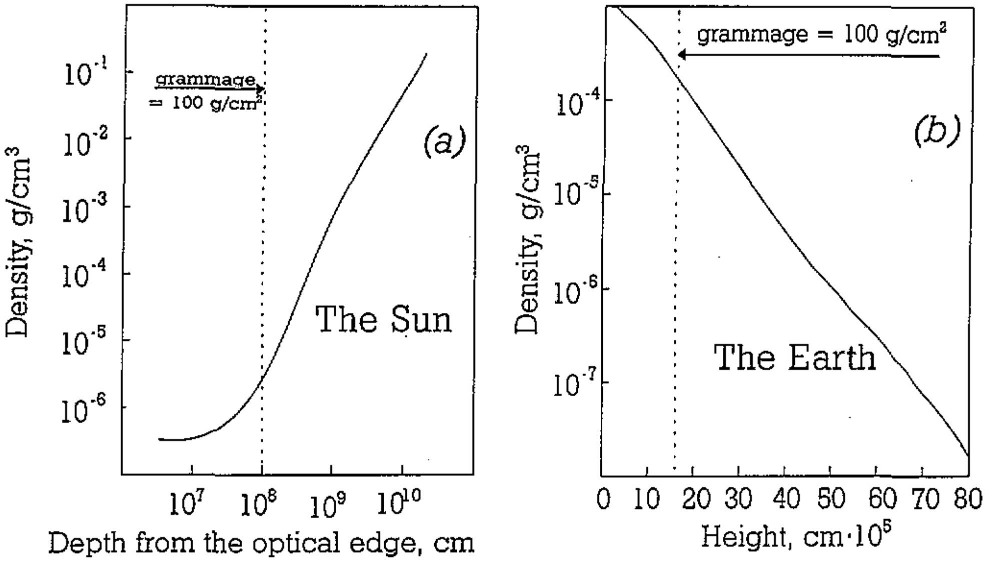

Figure 3. The densities of the solar corona (Spruit 1974) and the Earth's atmosphere (Allen 1973). The boundaries shown correspond to a thickness of matter of 100 g cm^{-2} calculated for a particle coming from infinity.

effect takes place at higher energies, because the solar gas density is very low. In figure 3 the densities of the solar corona against distance inside the optical edge of the Sun (Spruit 1974) and the Earth's atmosphere against distance from the surface (Allen 1973) are shown. For protons coming from infinity, the boundaries, corresponding to a thickness of matter of 100 g cm^{-2}, are also shown (the mean-free-path length of high-energy protons against pp collisions is 80–90 g cm^{-2}). It is seen that for the Earth's atmosphere such a boundary is reached at a height of ~16 km, where the density is ~2×10^{-4} g cm^{-3}; for the Sun the corresponding depth is ~10^8 cm from the optical edge and the density is ~2×10^{-6} g cm^{-3}. The densities of the solar and Earth's atmospheres at the 100 g cm^{-2} level differ by more than two orders of magnitude, therefore the steepening of the solar neutrino flux due to this effect takes place at energies above 10 TeV.

The second effect is the attenuation of the solar neutrino flux due to neutrino absorption in solar matter. The reduced neutrino flux is:

$$I_\odot(>E)=\int_E^\infty \frac{\gamma I_0(>E')}{E'}\,\mathrm{d}E'\,\frac{2}{R_\odot^2}\int_0^{R_\odot}\exp(-K(R,E'))R\,\mathrm{d}R\ (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}) \tag{7}$$

where $I_0(>E)$ is given by formula (4), R is the 'impact parameter' shown in figure 2, and $K(R,E)$ is the attenuation parameter for a neutrino of energy E passing at a distance R from the solar centre.

The attenuation parameter $K(R,E)$ is given by:

$$K(R,E)=\frac{2\sigma(E)}{m_\mathrm{p}}\int_0^{\sqrt{(R_\odot^2-R^2)}}\rho[(R_\odot^2+l^2-2l\sqrt{(R_\odot^2-R^2)})^{1/2}]\,\mathrm{d}l \tag{8}$$

where the integral is taken along the neutrino path, $\sigma(E)$ is the neutrino–nucleon

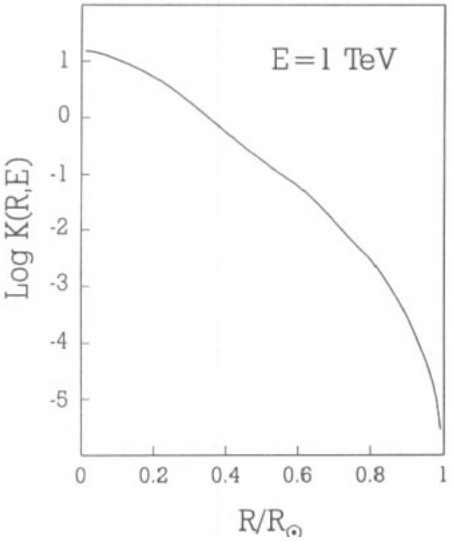

Figure 4. The attenuation parameter of the neutrino flux (8) against the 'impact parameter'; it illustrates the absorption of the 1 TeV neutrinos in solar matter.

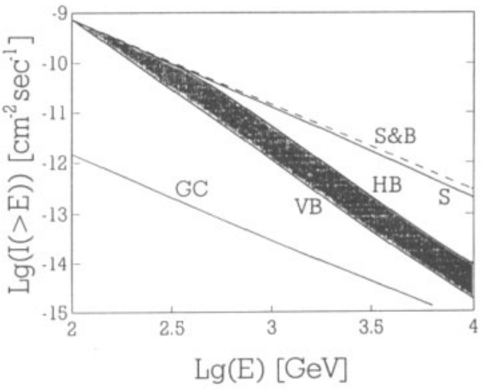

Figure 5. The estimated integral neutrino fluxes (solid lines) from the Sun (S), Galactic Gentre (GC), and the vertical (VB) and horizontal (HB) atmospheric background (e.g. Allkofer *et al* 1978, Volkova 1990) for a detector with 0.5° angular resolution. The dashed line (S&B) represents the solar and atmospheric fluxes without the neutrino absorption effect in solar matter and without the effect of steepening of the atmospheric neutrino flux (calculated using (4) and (5)).

cross section, m_p is the proton mass, and $\rho(R)$ is the solar density versus distance from the centre.

In figure 4 the attenuation parameter $K(R, E)$ versus R is shown for a neutrino energy of $E = 1\,\mathrm{TeV}$. A neutrino–nucleon cross section $\sigma(E) = 0.8 \times 10^{-38}$ $(E\,\mathrm{GeV}^{-1})$ cm^2, increasing with energy up to 4 TeV, was used (Eichler 1978, Gaisser 1990) and the solar density distribution $\rho(R)$ was taken from Allen (1973). In fact, the absorption effect is negligible; only a small part (<15%) of the cross-sectional area of the Sun around the centre is opaque for neutrinos of ~1 TeV.

The calculated neutrino flux from the Sun and background estimation for the ≈0.5° angular resolution detector are shown in figure 5. The dashed line represents the solar and atmospheric neutrino fluxes (S&B), which have been calculated using (4) and (5) for the following parameters: $k = 1\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{1.7}$, $\gamma = 1.7$ and for φ_ν we took value 0.023 (Berezinsky *et al* 1985). The solar neutrino flux S (solid line) was calculated taking into account the neutrino absorption effect in solar matter. The solid lines VB and HB are the vertical and horizontal atmospheric background fluxes, respectively. One can see that for the energy range ⩽200 GeV the flux/background ratio for solar neutrinos is ≈1. For the energy range ⩾200 GeV this ratio is increasing quickly, so the solar neutrino flux could be detected even with >0.5° angular resolution detector.

We have also calculated neutrino flux from the Galactic Centre (GC)—possibly one of the powerful neutrino sources. The comparison with the background flux (for the same assumptions as for formula (6)) gives:

$$I_{GC}(>E)/I_b(>E) = (1-\alpha^{\gamma})x/\lambda \approx 2\times10^{-3} \tag{9}$$

where x is the thickness of matter in the direction of the Galactic Centre, and λ is the proton mean-free-path length. As is illustrated in figure 5, the neutrino flux from the Galactic Centre direction is too small relative to the atmospheric background in the energy region 100 GeV–10 TeV.

Summarizing, we can say that a considerable excess of solar neutrino flux over the atmospheric background takes place at a comparatively low energy (~1 TeV), which gives a good possibility for observations in future neutrino experiments.

4. Discussion and conclusion

At present, the existing neutrino experiments can reach ~0.5° angular resolution (e.g. the MACRO detector (MACRO Collaboration 1987)), but the masses of the detectors are too small to get a reasonable counting rate of VHE neutrinos from the Sun (which probably exceeds estimated fluxes from the other local sources). For example, the expected event rate is of the order of one per year for the DUMAND-like array.

The presented calculations are in agreement with results obtained independently by Seckel *et al* (1991). They estimated the fluxes of neutrinos, γ-rays, antiprotons, neutrons and antineutrons as a result of interactions of high-energy cosmic rays with the solar atmosphere. Their main conclusions are: (i) the high-energy γ-ray flux should be detected by the EGRET instrument of the Compton Gamma Ray Observatory; (ii) the large neutrino detectors, e.g. GRANDE and DUMAND, should detect about one event per year, which is comparable with the background counting rate within the angular resolution (1°).

New possibilities for very high-energy neutrino astronomy appear with the development of the next generation of neutrino telescopes. Neutrino astronomy of point extraterrestrial sources will start when the detection technology permits us to reach a reasonable counting rate at an energy of $\geqslant$1 TeV. This is the threshold energy, due to two reasons, direction and energy discrimination. In this case the solar neutrino flux should be used as a 'standard candle' of high-energy neutrino astronomy for the detector calibration. The positive circumstance is also that the solar neutrino flux exceeds considerably the atmospheric background at an energy of about 1 TeV, therefore such neutrino flux should be detected even with a >0.5° angular resolution detector. Although the present experimental devices are not able to detect that neutrino flux, we believe the VHE solar neutrinos will be a matter of interest in the not too distant future.

We suggest some more possibilities for using the measured solar neutrino flux. Such observations could yield useful information about the behaviour of the neutrino–nucleon cross section at energies far beyond the range of present and near-future accelerators. The neutrino flux could also be used to understand solar deep layers and the nucleus.

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References

Allen C W 1973 *Astrophysical Quantities* (London: Athlone) p 179 (Russian Edition)
Allkofer O C *et al* 1978 *Proc. DUMAND Summer Workshop* (*La Jolla*)
Barwick S, Halzen F, Lowder D, Miller T, Morse R, Price P B and Westphal A 1992 *J. Phys. G: Nucl. Part. Phys.* **18** 225
Berezinsky V S, Castagnoli C and Galeotti P 1985 *Nuovo Cimento* **8C** 185
Berezinskii V S, Bulanov S V, Dogiel V A, Ginzburg V L and Ptuskin V S 1990 *Astrophysics of Cosmic Rays* ed V L Ginzburg (Amsterdam: North-Holland) p 326
Eichler D 1978 *Astrophys. J.* **222** 1109
Gaisser T K 1990 *Cosmic Rays and Particle Physics* (Cambridge: Cambridge University Press) p 111
MACRO Collaboration 1987 *Proc. 20th Int. Cosmic Ray Conf.* (*Moscow*) **6** 500
Moskalenko I V, Karakula S and Tkaczyk W 1991 *Astron. Astrophys.* **248** L5
Seckel D, Stanev T and Gaisser T K 1991 *Astrophys. J.* **382** 652
Sobel H 1991 *Proc. 3rd Int. Workshop on Neutrino Telescopes* (*Venice, 1991*) ed M Baldo Ceolin p 189
Spruit H C 1974 *Solar Phys.* **34** 277
Stecker F W 1979 *Astrophys. J.* **228** 919
Volkova L V 1990 *Sov. J. Nucl. Phys.* **6** 784