Expected neutrino signal from supernova remnant RX J1713.7-3946 and flavor oscillations

Maria Laura Costantini[a] and Francesco Vissani[b]
[a] *Universitá dell'Aquila, L'Aquila, Italia and INFN*
[b] *INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italia*

Abstract

We consider the impact of oscillations on 1-200 TeV neutrinos expected from RX J1713.7-3946. After a description of the nature of the source, we obtain a prediction for the neutrino fluxes, based on the intense gamma ray flux first seen by CANGAROO and recently measured by H.E.S.S. experiment. We study the effect of 3 flavor oscillations in detail and consider the impact on the muon flux induced by these high energy neutrinos, potentially observable by a neutrino telescope located in the Northern hemisphere. A detector in the Mediterranean with an effective area of 1 km^2 and unit detection efficiency should be able to see a signal of about 10 muons per year.

Introduction

The search for high energy cosmic neutrinos has a long history, tightly connected with the history of cosmic rays. The hope of a happy end is linked to neutrino telescopes presently in operation, in construction or in project. In the present work, we focus on a promising potential galactic source, the young supernova remnant RX J1713.7-3946, and calculate the expected muon signal using standard techniques [1, 2].

We begin by a description of this object (sect. 1), and state the predicted neutrino flux in sect. 2. In sect. 3, we evaluate precisely the impact of three flavor oscillations on the flux. The effect of the absorption of the high energy part of the flux in the Earth and of the live-time of observation is considered in sect. 4. The muon signal in neutrino telescopes is studied in sect. 5. A summary of the result is offered in sect. 6.

1 A potential neutrino source

In this section, we recall the motivations of interest in supernova remnants, and a number of recent facts that suggest that a specific SNR, RX J1713.7-3946 (G347.3-0.5), is a promising source of high energy neutrinos.

SNR are likely to act as accelerators of cosmic rays (CR). This suspicion was raised in 1934 [3] and convincingly supported thirty year later [4] on the basis of energetics: if several percents of the energy injected by one supernova ($\mathcal{E} \sim 10^{51}$ erg) go in CR acceleration, the losses from the Galaxy can be compensated. Two monographs, appeared in 1984 and 1990, offer still very actual summaries of the astrophysics of cosmic rays [1] and the connections with particle physics [2]. To a certain extent, the theory of acceleration of CR in SNR is still in evolution, but the generic expectations are stable: the cosmic ray flux at the SNR is expected to be a power law spectrum:

$$F_p = K \cdot E^{-\Gamma} \tag{1}$$

with index $\Gamma = 2.0 - 2.4$ and maximal energy $E_{p,max}$ possibly as large as several PeV, as suggested by 'knee' of the CR spectrum seen with extensive air showers arrays. Due to galactic magnetic fields, we cannot trace back CR to their source directly, but we can reveal sources if CR interact with some dense target (cosmic beam-dumps). The CR would partially fill the dense region, their interactions would produce mesons, which would eventually decay yielding observable gamma and neutrino radiation. The best case is a molecular cloud near to a young SNR [5, 6, 7].

There are converging indications that this happens in one specific SNR visible in the Southern sky, RX J1713.7-3946. Let us recall the main points: (*i*) A strong X ray source has been discovered there [8], that is compatible with a core collapse SN exploded in A.D. 393 at a distance of about 1 kpc [9]. (*ii*) The SNR is probably interacting with a molecular cloud, at about the same distance [10]. This was observed through the CO molecule; 21 cm hydrogen line observations corroborate these indications [11]. (*iii*) A large portion of the X-radiation comes from the same region where the cloud happens to be, the column density that produces X-ray absorption is compatible with the observed molecular cloud, and interesting details are continuing to emerge [12, 13, 14, 15, 16, 17, 18]. The interpretation of the X-rays as synchrotron radiation from 100 TeV electrons is compatible with ATCA radio observations. (*iv*) But most interestingly, the CANGAROO team did observe TeV gamma rays since several years [19]. This suggested this source as a CR accelerator [20]. Later it was claimed [21] that the only likely mechanism to produce the bulk of gammas is the hadronic one (namely, π^0's from proton interactions). Recently, the H.E.S.S. experiment also reported on the observation of an intense source of gamma rays, with energy in the TeV-10 TeV energy range [22]. This adds support to the overall picture, and (already with the first data) offers a precise determination of the photon flux.

One could perhaps argue that none of the items discussed above, taken alone, seems to be conclusive. Also, the interpretation outlined here has to face a number of controversial points: the distance of the object [23], the compatibility with EGRET bound [24] (but see [25]) and the uniqueness of the hadronic hypothesis [26] have been all questioned. Furthermore, the spectra of CANGAROO and H.E.S.S. do not agree well (see [22]); this may be an indication that the systematic error for energy measurement of one or both experiments has an underestimated uncertainty (note however that CANGAROO has measured photons from the N-W rim, while H.E.S.S. measures the spectrum for the photons coming from a wider region). All these objections have to be seriously considered. However, the fact remains that RX J1713-3946 is a very promising case for a cosmic beam dump, where the available observations seem to meet theoretical expectations. In this case, the observed gamma radiation must be accompanied by neutrinos. In view of the interest in neutrino telescopes located the Northern hemisphere, this is a very important conclusion. Actually, we would dare to say that RX J1713-3946 is at present the most definite hope (although not necessarily 'the best') of a successful observation of cosmic neutrinos. For other possible sources of TeV neutrinos in the Galaxy, see [27].

As a matter of fact, there is already a specific calculation of the neutrino signal from this source [28]. We improve on this calculation in the following points: we consider deviations from the hypothesis $\Gamma = 2$, we include the effect of live-time of measurement and of neutrino absorption, we describe the interactions at next-to-leading order (NLO) in QCD, and most importantly, we consider the occurrence of neutrino oscillations.

2 Secondary gamma and neutrino radiation

The connection between gamma and neutrino is described in [1] (see in particular ref.[38] of Chapter VIII there, or tab.1 of [29]) and in [2]. Here, we will follow this last reference quite closely, and describe the relation between secondary gamma and neutrino radiation using the formulæ of cascade theory.[1] Assuming scaling, CR primaries and secondaries (photons, neutrinos and antineutrinos) have the same type of spectrum. So we take as injection proton spectrum a power law with spectral index Γ in the range $2 - 2.4$ as in eq. (1), and similarly for neutrinos. The photon spectrum from the cascade $p \to \pi^0 \to \gamma$ is

$$F_\gamma = \frac{\Delta X}{\lambda_p} \cdot \frac{Z_{p\pi^0}(\Gamma)}{\Gamma} \cdot F_p \tag{2}$$

where ΔX is the column density traversed by the protons and λ_p is the interaction length of CR. The effects of the π^0 distribution (determined by strong interactions) are lumped into the spectrum-weighted momenta, $Z_{p\pi^0}$ in this example. Similar expressions hold for neutrinos, as a sum of several (slightly more complicated) terms that describe the possible branches of the π and K cascades.[2] In summary, the flux of the neutrinos of any species is just proportional to the photon flux:

$$F_\nu = k \cdot F_\gamma, \qquad \nu = \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e \tag{3}$$

through a proportionality coefficient k that depends on the type of neutrino and on the spectral index. Numerical values are given in table 1. In this manner, the neutrino fluxes are *predicted* in terms of the measured photon flux.

spectr. index	ν_μ/γ	$\overline{\nu}_\mu/\gamma$	ν_e/γ	$\overline{\nu}_e/\gamma$
2.0	0.50	0.50	0.30	0.22
2.1	0.46	0.46	0.29	0.19
2.2	0.43	0.43	0.28	0.18
2.3	0.40	0.41	0.26	0.16
2.4	0.37	0.38	0.25	0.15

Table 1: *Fluxes of neutrinos and antineutrinos originating from pion and kaon decay, relative to the photon flux. The latter is assumed to be a power spectrum with value of index indicated in the* 1^{st} *column.*

H.E.S.S. data [22] in the range $E = 1 - 10$ TeV are well described by a power spectrum with $\Gamma = 2.19 \pm 0.09 \pm 0.15$, that is in good agreement with theoretical expectations. For our purposes, and since these measurements are going to be improved soon in the future, we shall limit ourselves to set $\Gamma = 2.2$, modeling the photon flux as follows:

$$F_\gamma = 1.7 \times 10^{-11} \ \left(\tfrac{E}{\text{TeV}}\right)^{-2.2} \tfrac{1}{\text{TeVcm}^2\text{s}} \tag{4}$$

The corresponding neutrinos fluxes are:

$$\begin{aligned} F^0_{\nu_\mu} &= 7.3 \times 10^{-12} \ \left(\tfrac{E}{\text{TeV}}\right)^{-2.2} \tfrac{1}{\text{TeVcm}^2\text{s}} \\ F^0_{\overline{\nu}_\mu} &= 7.4 \times 10^{-12} \ \left(\tfrac{E}{\text{TeV}}\right)^{-2.2} \tfrac{1}{\text{TeVcm}^2\text{s}} \\ F^0_{\nu_e} &= 4.7 \times 10^{-12} \ \left(\tfrac{E}{\text{TeV}}\right)^{-2.2} \tfrac{1}{\text{TeVcm}^2\text{s}} \\ F^0_{\overline{\nu}_e} &= 3.0 \times 10^{-12} \ \left(\tfrac{E}{\text{TeV}}\right)^{-2.2} \tfrac{1}{\text{TeVcm}^2\text{s}} \end{aligned} \tag{5}$$

where the superscripts ^{0} remind us that oscillations are not included. In this approximation, the flux of tau (anti) neutrinos at the source is expected to be negligible.

An important question is which is the uncertainty on the neutrino/photon ratio. A primary cause is the uncertainty in the photon flux from π^0s. Beside experimental errors, it is possible that the gamma radiation has other, non-hadronic components; this will be better quantified with more data and when the morphology of the source will be understood in detail. The uncertainties in column density ΔX disappear when we consider the ratio. Other causes of uncertainty include the one on hadronic interactions (=the spectrum-weighted momenta) and the neglected decay channels, but again this should have a weaker impact on the ratio. If we consider as an analogy the predictions of the atmospheric neutrino fluxes [30], we are lead to believe that the neutrino fluxes we deduced should have an accuracy of 20% or better, at

[1] The situation is simpler than for the Earth atmosphere, since the muons originating from the leptonic decays of charged pions or kaons do not interact. The same is true for the photons from neutral pion and eta decays, since the molecular cloud is very thin in comparison with the radiation length $X_0 \sim 60$ g/cm^2 for hydrogen (=the source is "gamma-transparent"). Indeed, a cloud of a few parsec and with at density of few times 100 particles/cm^3 has a column density around 0.005 g/cm^2 or smaller.

[2] For instance, since a ν_e comes from $p \to \pi^+ \to \mu^+ \to \nu_e$, we have $F_{\nu_e} = \Delta X/\lambda_p \cdot Z_{p\pi^+}(\Gamma) \cdot f_{\pi^+\mu^+\nu_e}(\Gamma) \cdot F_p + ...$, where $f_{\pi^+\mu^+\nu_e}$ is a function that can be found in Sect. 7.1 of the book [2], and '...' stands for the additional K^+ contribution, weighted with the branching ratio into leptons, $BR = 0.635$. Values of the spectrum-weighted momenta are obtained from fig. 5.5 of the same book; in this way, we introduce an error at the few % level.

least in the energy region of $1-10$ TeV. Another way to argue for such an accuracy is to compare the results of our tab.1 with those in [29]. Now, if one agrees that an accuracy of 20 % is reached, the effects of oscillations *must be included*, since as we will see they are of the order of 50%.

3 Three flavor oscillations of SNR neutrinos

Now, we pass to describe the effects of neutrino oscillations. From the theoretical point of view, the situation is particularly simple, since the phases of oscillations are really very large:

$$\varphi \sim 3\cdot 10^8 \left(\frac{\Delta m^2}{8\cdot 10^{-5}\ \mathrm{eV}^2}\right)\left(\frac{D}{1\ \mathrm{kpc}}\right)\left(\frac{10\ \mathrm{TeV}}{E_\nu}\right) \quad (6)$$

The conclusion is that we just need to consider averaged vacuum[3] oscillations [31, 32, 34, 33, 35]. The expression of the probability of flavor transformation is given in function of the mixing matrix $U_{\ell j}$:

$$P_{\ell\ell'} = \sum_j |U^2_{\ell j}|\cdot|U^2_{\ell' j}|, \quad (7)$$

with $\ell,\ell' = e,\mu,\tau$. The probabilities are the same for neutrinos and antineutrinos. After propagation, the neutrino fluxes become:

$$F_\ell = \sum_{\ell'=e,\mu,\tau} P_{\ell\ell'}\ F^0_{\ell'} \quad (8)$$

Adopting the standard decomposition of $U_{\ell j}$ [38], we can summarize the present experimental information as: $\theta_{12} = 32.5^\circ \pm 2^\circ$ (solar neutrinos and KamLAND), $\theta_{23} = 45^\circ \pm 10^\circ$ (atmospheric neutrinos and K2K), $\theta_{13} = 0^\circ \pm 10^\circ$ (CHOOZ), $\delta_{\rm CP} = 0^\circ - 360^\circ$ (namely, we do not know the CP violating phase $\delta_{\rm CP}$, but it appears always with θ_{13}). In a reasonable approximation, the symmetric matrix P (with elements $P_{\ell\ell'}$) is given by:

$$P \sim \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ & 0.4 & 0.4 \\ & & 0.4 \end{pmatrix} \quad (9)$$

An interesting question is which deviations we can expect. Let us assume that there are not main causes of systematic errors. Since the formal errors in the angles are quite small, it is useful to expand in linear approximation in θ_{12}, $\cos 2\theta_{23}$ and θ_{13} around the central point $\theta_{12} = 32.5^\circ$, $\cos 2\theta_{23} = 0$ and $\theta_{13} = 0^\circ$, getting:

$$P \simeq \begin{pmatrix} 1-\frac{x}{2} & \frac{x}{4}+y & \frac{x}{4}-y \\ & \frac{1}{2}-\frac{x}{8}-y & \frac{1}{2}-\frac{x}{8} \\ & & \frac{1}{2}-\frac{x}{8}+y \end{pmatrix} \quad (10)$$

where we define $x = \sin^2 2\theta_{12}$, $y = \epsilon_{23} + \epsilon_{13}$ and:

$$\begin{cases} \epsilon_{12} = 2\sqrt{x(1-x)}\cdot\delta\theta_{12} \\ \epsilon_{23} = x/4\cdot\cos 2\theta_{23} \\ \epsilon_{13} = \sqrt{x(1-x)}/2\cdot\delta\theta_{13}\cdot\cos\delta_{\rm CP} \end{cases} \quad (11)$$

Thus, the three uncertainty in P, respectively due to the angles θ_{12}, θ_{23} and $\delta_{\rm CP}$ (setting $\delta\theta_{13} = 10^\circ$), are:

$$\begin{aligned} \delta P \simeq \pm 2.7\% \begin{pmatrix} -1 & 1/2 & 1/2 \\ & -1/4 & -1/4 \\ & & -1/4 \end{pmatrix} + \\ +(\ \pm 3.6\%\ \ \pm 3.3\%\ ) \begin{pmatrix} 0 & 1 & -1 \\ & -1 & 0 \\ & & 1 \end{pmatrix} \end{aligned} \quad (12)$$

From previous equation we see that the variations are rather small. The main effect when we are interested to muon signal is due to the latter two uncertainties. Combining them in quadrature we obtain the numerical expression:

$$\delta P_{\mu\mu} = -\delta P_{e\mu} = \pm 5\% \quad (13)$$

which means that the errors introduced by the uncertainties in the parameters of oscillations are negligible. (It means also that there is little hope to learn anything useful on 3 flavor oscillations).

Thus we evaluate oscillations with mixing angles at central values. Using the fluxes in eq. (5), we arrive at the following expectation for neutrino fluxes at Earth:

$$\begin{aligned} F_{\nu_\mu} &= 3.9\times 10^{-12}\ \left(\tfrac{E}{\mathrm{TeV}}\right)^{-2.2}\ \tfrac{1}{\mathrm{TeV cm^2 s}} \\ F_{\overline{\nu}_\mu} &= 3.5\times 10^{-12}\ \left(\tfrac{E}{\mathrm{TeV}}\right)^{-2.2}\ \tfrac{1}{\mathrm{TeV cm^2 s}} \\ F_{\nu_e} &= 4.3\times 10^{-12}\ \left(\tfrac{E}{\mathrm{TeV}}\right)^{-2.2}\ \tfrac{1}{\mathrm{TeV cm^2 s}} \\ F_{\overline{\nu}_e} &= 3.3\times 10^{-12}\ \left(\tfrac{E}{\mathrm{TeV}}\right)^{-2.2}\ \tfrac{1}{\mathrm{TeV cm^2 s}} \end{aligned} \quad (14)$$

They are the same within 20%. The expected flux of tau (anti) neutrinos is the same as the flux of muon (anti) neutrinos, which could lead to interesting signals. However, in the following we focus just on the *muon* neutrino and antineutrino fluxes. They give rise to muons, thus offering a simple way to emphasize an observable signal.

[3]The MSW [36] effect does not modify the conclusion for two different reasons: (1) in the vicinity of the star, the matter potential is negligible in comparison to the vacuum term because of the small density in the molecular cloud; (2) inside the Earth, the converse happens; the matter potential is so large that any further oscillation is suppressed. See also [37].

4 Live-time and absorption in the Earth

During the sidereal day which lasts $2 \times \tau = 23^h 56^m 4^s$, a neutrino telescope can observe a source only when the overwhelming background atmospheric muons is absent. In first approximation, this condition is met when the source is below the horizon. Taking the Earth's axis of rotation as $\hat{z}$ direction, and $\hat{x}$ axis in such a manner that the source is in the xz plane, the direction of the source is $\hat{s} = (\cos\delta, 0, \sin\delta)$ (δ is the declination, $\delta = -39°46'$ in our case) and the one of the telescope is $\hat{t} = (\cos\phi\cos(\pi t/\tau), \cos\phi\cos(\pi t/\tau), \sin\phi)$ (ϕ is the latitude). ANTARES has $\phi = 42°50'$ (that we adopt for numerical example), NEMO or NESTOR are more South, about $\phi = 36°30'$ and $\phi = 37°33'$ respectively, whereas BAIKAL is more North $\phi = 51°50'$. The cosine of the zenith angle $\cos\theta_Z \equiv \hat{s}\cdot\hat{t}$ is thus:

$$\cos\theta_Z = \sin\delta\sin\phi + \cos\delta\cos\phi\cos(\pi t/\tau) \qquad (15)$$

The origin of the time $t = 0$ is the point of highest altitude (the apex), and conversely, the lowest altitude is reached when $t = \tau$. The source becomes observable after the time τ_0 that satisfies $\cos\theta_Z(\tau_0) = 0$. This condition can be satisfied if $90° - |\delta| \geq \phi \geq -(90° - |\delta|)$, that happens to be true for all detectors except BAIKAL. In other words, RX J1713-3946 is always observable for BAIKAL (it is always below the horizon, $\phi - \delta > 90°$), whereas for the other detectors, it is observable for a fraction of time $f_{liv} = 1 - \tau_0/\tau$. This can be written:

$$f_{liv} = 1 - \frac{\arccos(-\tan\delta\ \tan\phi)}{\pi} \qquad (16)$$

For ANTARES this is 78 %, whereas for NEMO and NESTOR this is a bit less, 71 % and 72 % respectively.

There is another effect that diminishes the number of observable events: High energy neutrinos are absorbed in the Earth before reaching the detector. This effect depends on the column density x seen by neutrinos. When $\cos\theta_Z \leq 0$, we have:

$$x = -2R_\oplus \cos\theta_Z \cdot \overline{\rho}_\oplus(\cos\theta_Z) \qquad (17)$$

This varies with time according to eq. (15). Here, $R_\oplus = 6.371 \cdot 10^8$ cm is the radius of the Earth, and $\overline{\rho}_\oplus$ (in gr/cm^3) is the average Earth density along the line of sight, obtained using the PREM model [39]. Now we can define the neutrino absorption coefficient a_ν and its time average $\overline{a}_\nu$ as:

$$a_\nu(t, E) = 1 - e^{-N_A x(t)\sigma(E)}$$
$$\overline{a}_\nu(E) = \frac{\int_{\tau_0}^{\tau} dt\ a_\nu(t,E)}{\tau - \tau_0} \qquad (18)$$

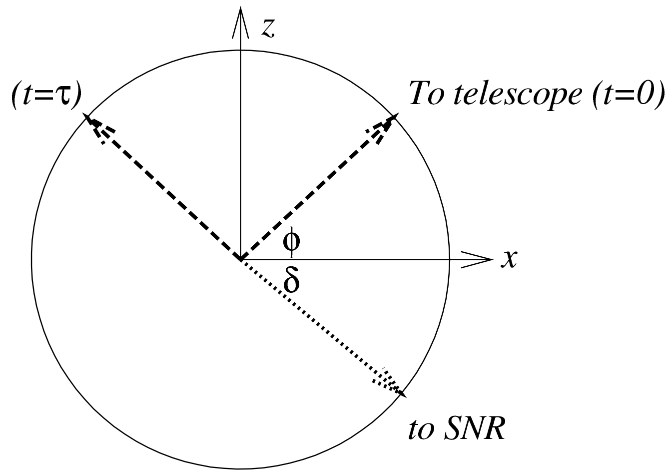

Figure 1: *Projection of the Earth in the xz-plane. The versor of the SNR (with direction "to SNR") is shown. Also shown the versor of the telescope at the times $t = 0$ and $t = \tau$, when it lies in the xz-plane.*

where N_A is the Avogadro number and σ the effective cross section of neutrino absorption. The main part is due to CC interactions; NC interactions increase the absorption coefficient by a small amount.[4] This conclusion is in agreement with what found in [41]. For antineutrinos, the calculations are exactly the same.

For the interactions (deep inelastic scattering) we adopt the recently calculated MRST2004 partons [42] and work at NLO in QCD [43]. Let us note that the measurements of HERA at $s = 4E_pE_e \equiv 2M_pE_\nu$ with $E_\nu \sim$ 50 TeV give us confidence that we have an accurate description of the interaction cross section in the relevant energy range. Small modifications due to nuclear medium (average rock nuclei in this section, water nuclei in the next one) are described using the simple prescriptions of [44].

5 Signal in neutrino telescopes

Charged-current interactions of ν_μ and $\overline{\nu}_\mu$ produce muons and antimuons that can be observed underground. This is the simplest observable for a cosmic source of high-

[4]The NC cross section is $\sim$ 1/3 of the CC one for relevant energies. At first, one could guess that $\sigma = \sigma_{cc} + \sigma_{nc} \equiv \sigma_{tot}$. But NC interactions differ from CC interactions since they do not absorb a neutrino; rather, they lower its energy ('neutrino regeneration'). We can estimate this effect by replacing σ_{nc} with $\sigma_\Gamma \equiv \sigma_{nc}(1 - Z_\Gamma)$, where setting $E' = E/(1-y)$ we define $Z_\Gamma(E)\ \sigma_{nc}(E) \equiv \int dy\ (1-y)^{(\Gamma-1)}\ d\sigma_{nc}(E', y)/dy$ [40]. For $\Gamma \approx 2.2$, σ_Γ is about 10 % of σ_{cc}. Using in the exponent of eq. (18) $\sigma \equiv \sigma_{cc} + \sigma_\Gamma$ with $\Gamma = 2.2$, we conclude that $\overline{a}_\nu(E)$ increases by about 5 %.

energy neutrinos, and it is known since long [45]. The reason why we prefer to concentrate on this observable is that the underwater detectors can achieve a very good angular resolution, perhaps better than one degree. This offers a very effective tool to reject the background of atmospheric neutrinos in neutrino telescopes.

The number of muons and antimuons reaching an area A in a time of observation T is:

$$N_{\mu+\overline{\mu}} = f_{liv} \cdot A \cdot T \cdot \int_{E_{th}}^{\infty} dE_\nu \; F_{\nu_\mu}(E_\nu) \times \\ \times Y_\mu(E_\nu, E_{th}) (\; 1 - \overline{a}_{\nu_\mu}(E_\nu) \;) + (\nu_\mu \to \overline{\nu}_\mu) \quad (19)$$

where E_ν is the energy of the neutrino at the point of interaction and E_{th} is the minimal muon energy that can be detected, and "$\nu_\mu \to \overline{\nu}_\mu$" stands for the contribution of the antineutrinos (same expression using antineutrino flux, cross section, and absorption coefficient). Whenever needed, we take as reference values:

$$A = 1 \text{ km}^2, \; T = 1 \text{ solar y}, \; E_{th} = 50 \text{ GeV} \quad (20)$$

Neutrino fluxes F and absorption coefficients $\overline{a}_\nu$ are defined in eqs. (5,14) and (18). Finally, the probability to yield a muon Y_μ can be calculated by the interaction cross sections and the muon range in water in the following manner:

$$Y_\mu = N_A \int_{E_{th}}^{E_\nu} dE_\mu \frac{d\sigma_{cc}}{dE_\mu}(E_\nu, E_\mu) \; R(E_\mu, E_{th}) \quad (21)$$

where N_A is the Avogadro number; similarly for antineutrinos. The muon range $R(E_\mu, E_{th})$ can be obtained integrating the equation:

$$\frac{dR}{dE_\mu} = -\frac{1}{\alpha + \beta E_\mu} \quad (22)$$

where the dependence of α and β on E_μ in water is taken from ref. [1].[5] On passing, we remark that occasionally the calculation of the the cross sections σ_{cc} and of the yields Y_μ are done using the DIS formula at the leading order (LO), but using the partons calculated at NLO. This procedure is not consistent, and the cross sections and yields obtained in this way are overestimated by 10% at 20 TeV, and by 25% at 1 PeV.

The parent spectrum (distribution of the events in the energy of neutrinos at the interaction point) is shown in Figure 2 for five cases: 1. a fully 'idealized' case; 2.−4. the three cases when oscillations, absorption and live-time are considered once at the time; 5. the case when all three effects are included. The typical energies are in the range 1-200 TeV, after inclusion of absorption (that produces a downward shift). For $E_\nu = 50$ GeV−1 PeV, these effects reduce the number of events by:

$$\text{abs.: } 0.81, \; \text{liv.: } 0.78, \; \text{osc.: } 0.51 \quad (23)$$

The impact of all these effects, and in particular the one of oscillations, are rather important. In particular, the number of events expected for case 1. is:

$$N^{ideal}_{\mu+\bar{\mu}} = 29.1 \quad (24)$$

This number is compatible with the 41 events found in [28] (see fig. 1 there), when we consider that in [28] the spectral index is assumed to be very hard, $\Gamma = 2$. But after the inclusion of oscillations, absorption and live-time, the decrease is much stronger:

$$N_{\mu+\bar{\mu}} = 9.3 \quad (25)$$

This is the main result of the present work.

We present cumulative curves in Figure 3. These permit to rescale the above results if the maximal energy of

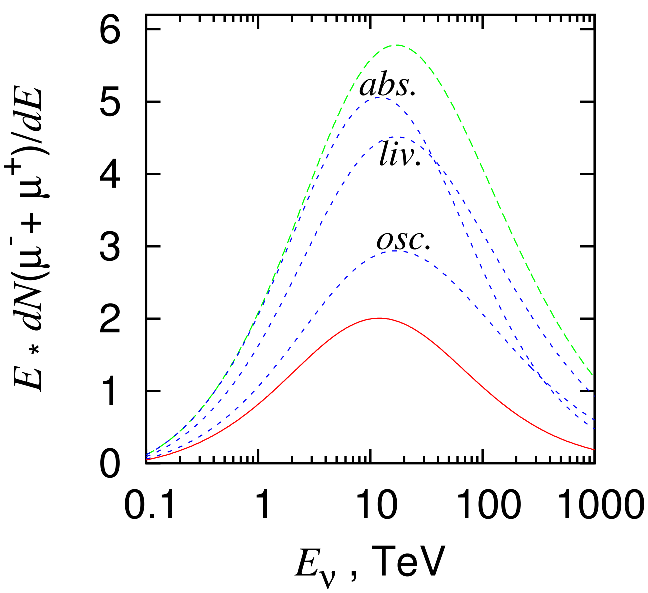

Figure 2: *Distribution of muons + antimuons above $E_{th} = 50$ GeV due the fluxes of eqs. (5) and (14), that pass through an area $A = 1$ km^2 in 1 yr. The higher curve is the 'idealized' case. The 3 middle ones show the impact of absorption ("abs."), live-time ("liv.") and 3 flavor oscillations ("osc."). The last effect is universal, whereas the first 2 effects are estimated for $\phi = 42°50'$. The lower curve includes all three effects.*

[5] We recall that in the approximation of constant coefficients, $R(E_\mu, E_{th}) = 1/\beta \log[(1 + E_\mu/\epsilon)/(1 + E_{th}/\epsilon)]$ with $\epsilon = \alpha/\beta$. In the energy range of interest this agrees at 10 % with the accurate result when $\alpha = 2.4 \cdot 10^{-3}$ GeV/cm and $\beta = 2 \times 10^{-6}$ cm^{-1}.

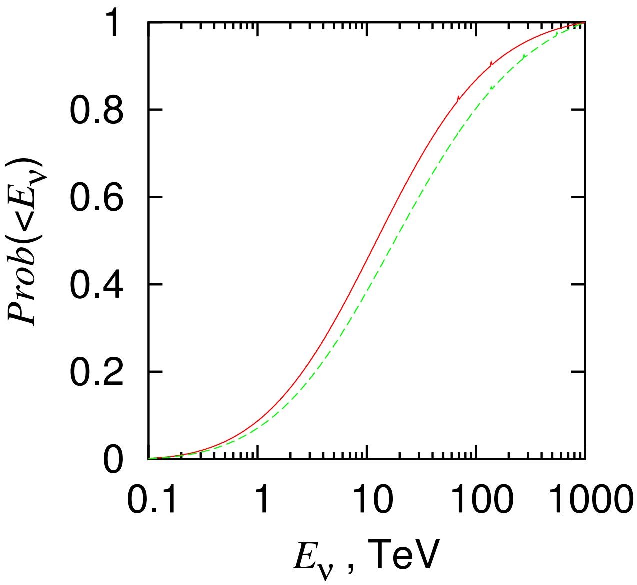

Figure 3: *Cumulative distribution of the number of muons + antimuons above $E_{th} = 50$ GeV. The curve displaced at high energies is the 'idealized' case (corresponds to the higher curve of fig.2) the other one includes the effects of absorption, live-time and 3 flavor oscillations (corresponds to the lower curve of fig.2).*

the neutrino spectrum (=the cut of the power spectrum) is lower than the value we allowed, $E_{\nu,max} = 1$ PeV. For instance, if we limit ourself to what we know from photons, we could believe that the cut in the neutrino energy happens as early as at 5 TeV. This would mean a dramatic reduction factor of 0.31 to be applied to the number in eq. (25). Instead, in the more realistic case when the proton spectrum is cut at the energy of the knee ($E_{p,max} = 3$ PeV), one expects a cut for the neutrino spectrum somewhere close to 250 TeV (and close to 0.5 PeV for gamma spectrum). This means that the number in eq. (25) should be diminished, but only by 5 %.

Finally, let us note that the numbers of eqs. (24) and (25) apply to a detector with unit efficiency of detection.[6]

6 Summary and discussion

The recent H.E.S.S. measurements support the view that RX J1713-3946 is a source of neutrinos with energies at TeV and above. Existing data already permit to predict the neutrino flux to a reasonable level of approximation. Future gamma-ray data should clarify the picture, and possibly reveal the extension of the power spectrum.

We calculated the expected number and distribution of neutrino events in underwater neutrino telescopes from RX J1713.7-3946. These calculations cannot be considered definitive for a number of reasons (e.g., CR are assumed to be solely protons, a power law spectrum is assumed, 'neutrino regeneration' is treated in the simplest approximation, only a perfect detector is considered). Also, we did not attempt to estimate the background, though this was done purposely: we believe that it should be estimated during detector operation, and we are aware of a number of theoretical uncertainties (generally on high energy part of atmospheric neutrinos flux [46], and more specifically on the prompt contribution).

However, we improved over the existing calculation of the neutrino signal from RX J1713-3946 [28] in several senses: we considered a deviation from strict equality $\Gamma = 2$, we treated the neutrino interactions at NLO, we estimated absorption in the Earth and live-time of data acquisition, and most importantly, we included 3 flavor oscillations. Our calculations, in particular eq. (25), suggest that a detector located in the Northern hemisphere should have an effective area of $\sim$ km^2 and/or a long data taking time in order to see RX J1713-3946 as a source of high-energy neutrinos.

We thank for pleasant discussions and help V. Berezinsky, A. Butkevich, M. Cirelli, P. Desiati, S. Dugad, W. Fulgione, P. Ghia, T. Montaruli, G. Navarra, I. Sokalsky, A. Strumia, R. Thorne, Y. Uchiyama.

References

[1] V.S Berezinsky, S.V. Bulanov, V.A. Dogiel, V.L. Ginzburg (ed.), V.S. Ptuskin, *Astrophysics of cosmic rays*, (1990, Russian edition 1984) North Holland

[2] T.K Gaisser, *Cosmic rays and particle physics*, (1990) Cambridge Univ. Pr.

[3] W. Baade, F. Zwicky, Phys. Rev. 45 (1934) 138

[4] V.L. Ginzburg, S.I. Syrovatsky, *Origin of Cosmic Rays* (1964) Moscow

[5] F.A. Aharonian, L.O'Drury, H.J. Völk, Astron. Astroph. 285 (1994) 645

[6] L.O'Drury, F.A. Aharonian, H.J. Völk, Astron. Astroph. 287 (1994) 959

[7] T. Naito, F. Takahara, J. Phys. G 20 (1994) 477

[6] In real detectors, the efficiency is usually included in the "effective area", that is an increasing function of the energy.

[8] E. Pfeffermann, B. Aschenbach, Proc. of *Röntgenstrahlung from the Universe* (1996) page 267, eds. Zimmermann, Trumper and Yorke

[9] Z.-R. Wang, Q.-Y. Qu, Y. Chen, Astron. Astroph. 318 (1997) L59

[10] NANTEN Collaboration, Y. Fukui *et al.*, Publ. Astron. Soc. Japan 55 (2003) L61

[11] B.-C. Koo *et al.*, astro-ph/0406450

[12] K. Koyama *et al.*, Publ. Astron. Soc. Japan 49 (1997) L7

[13] Y. Uchiyama, F.A. Aharonian, T. Takahashi, Astron. Astroph. 400 (2003) 567

[14] J.S. Lazendic *et al.*, Astroph.J. 602 (2004) 271

[15] T.G. Pannuti *et al.*, Astroph.J. 593 (2003) 377

[16] G. Cassam-Chenaï *et al.*, astro-ph/0407333

[17] J.S. Hiraga *et al.*, astro-ph/0407401

[18] H.J. Völk, E.G. Berezhko, L.T. Ksenofontov, astro-ph/0409453

[19] CANGAROO Collaboration, H. Muraishi *et al.*, Astron. Astroph. 354 (2000) L57

[20] Y.M. Butt, D.F. Torres, J.A. Combi, T. Dame, G.E. Astrophys.J.562 (2001) L167

[21] CANGAROO Collaboration, R. Enomoto *et al.*, Nature 416 (2002) 823

[22] H.E.S.S. Collaboration, F.A. Aharonian *et al.*, Nature 432 (2004) 75

[23] P. Slane *et al.*, Astrophy. J. 525 (1999) 357

[24] O. Reimer, M. Pohl, Astron. Astroph. 390 (2002) L43.

[25] T. Tanimori, presented at *SSI 2003*, e Conf CO307282:TTH07, in particular fig.7

[26] Y.M. Butt *et al.*, Nature 418 (2002) 499.

[27] W. Bednarek, G.Fiorella Burgio, T. Montaruli, astro-ph/0404534

[28] J. Alvarez-Muñiz, F. Halzen, Astroph.J. 576 (2002) L33

[29] V. Berezinsky, Nucl. Phys. B Proc. Suppl 19 (1991) 375 (Neutrino 1990)

[30] See e.g. T. K. Gaisser *et al.* Phys. Rev. D 54 (1996) 5578

[31] S. M. Bilenky and B. Pontecorvo, Phys. Rept. 41 (1978) 225

[32] R.M. Crocker, F. Melia, R.R. Volkas, Astroph.J. Suppl. 130 (2000) 339

[33] H. Athar, M. Jezabek and O. Yasuda, Phys. Rev. D 62 (2000) 103007

[34] R.M. Crocker, F. Melia, R.R. Volkas, Astroph.J. Suppl. 141 (2002) 147

[35] J.F. Beacom, N.F. Bell, D. Hooper, S. Pakvasa, T.J. Weiler, Phys.Rev. D 68 (2003) 0930005

[36] L. Wolfenstein, Phys. Rev. D 17 (1978) 2369; S. P. Mikheev and A. Y. Smirnov, Sov. J. Nucl. Phys. 42 (1985) 913

[37] C. Lunardini and A. Y. Smirnov, Phys. Rev. D 64 (2001) 073006

[38] PDG collaboration, Phys. Lett. B 529 (2004), 1. The decomposition of eq. 11.3 applies also to lepton mixing; the values of the leptonic angles are indicated in the text.

[39] A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Interiors 25 (1981) 297

[40] V.S. Berezinsky, A.Z. Gazizov, I.L. Rozental, G.T. Zatsepin, Sov. J. Nucl. Phys. 43 (1986) 406. See also E.V. Bugaev, S.P. Mikheyev, O.V. Suvurova, Vol I, Proc. of 24th ICRC (1995) 666

[41] A. L'Abbate, T. Montaruli and I. Sokalski, hep-ph/0406133

[42] A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, hep-ph/0410230.

[43] The needed `FORTRAN` programs are in `mrst02cc.f` (trivially modified), and can be found at the web site durpdg.dur.ac.uk/hepdata/mrs.html

[44] G. I. Smirnov, Eur. Phys. J. C 10 (1999) 239

[45] M.A. Markov, Proc. X Int. Conf. on HEP, Rochester (1960) 578; K. Greisen, Proc. Int. Conf. Instrum. for HEP, Berkeley (1960) 219; M.A. Markov, I.M. Zheleznykh, Nucl. Phys. 27. (1961) 385

[46] See e.g., G. Battistoni, A. Ferrari, T. Montaruli and P. R. Sala, Proc. of 28th ICRC (2003) 1399, hep-ph/0305208