GeV - PeV Neutrino Production and Oscillation in hidden jets from GRBs

Nissim Fraija *

Instituto de Astronomía, Universidad Nacional Autónoma de México, Circuito Exterior, C.U., A. Postal 70-264, 04510 México D.F., México

29 October 2013

ABSTRACT

Long gamma-ray bursts have been widely associated with collapsing massive stars in the framework of collapsar model. High-energy neutrinos and photons can be produced in the internal shocks of middle relativistic jets from core-collapse supernova. Although photons can hardly escape, high-energy neutrinos could be the only signature when the jets are hidden. We show that using suitable parameters, high-energy neutrinos in GeV - PeV range can be produced in the hidden jet inside the collapsar, thus demonstrating that these objects are candidates to produce neutrinos with energies between 1 - 10 PeV which were observed with IceCube. On the other hand, due to matter effects, high-energy neutrinos may oscillate resonantly from one flavor to another before leaving the star. Using two (solar, atmospheric and accelerator parameters) and three neutrino mixing, we study the possibility of resonant oscillation for these neutrinos created in internal shocks. Also we compute the probabilities of neutrino oscillations in the matter at different distances along the jet (before leaving the star) and after in vacuum, on their path to Earth. Finally, neutrino flavor ratios on Earth are estimated.

Key words: Long Gamma-ray burst: High-energy Neutrinos: – Neutrino Oscillation

1 INTRODUCTION

A number of different high-energy, $\gtrsim$ 1GeV, neutrino sources have been proposed in literature, that include active galactic nuclei (AGN), (Stecker et al. 1991; Szabo & Protheroe 1994; Nellen, Mannheim & Biermann 1993; Atovan & Dermer 2001; Alvarez-Muñiz & Mészáros 2004), gamma-ray bursts (GRBs) (Waxman & Bahcall 1997; Dermer & Atovani 2003; Razzaque, Mészáros & Waxman 2004; Murase et al. 2006; Gupta & Zhang 2007), supernova remnants (Alvarez-Muñiz & Halzen 2002; Costantini & Vissani 2005) and core collapse supernovae (Waxman & Loeb 2001; Wang et al. 2007), although long duration GRBs have been found to be tightly connected with core-collapse supernovae (Hjorth & et al. 2003; Stanek & et al. 2003). Properties of neutrino fluxes, energy range, shape of the energy spectra and flavor content depend on physical conditions in the sources. Neutrinos are useful for studying sources, especially when photons cannot escape directly. They could be the only prompt signatures of the "hidden" sources. These have been associated to core collapse of massive stars leading to supernovae (SNe) of type Ib,c and II with mildly relativistic jets emitted by a central engine, a black hole or a highly magnetized neutron star. Depending on the initial density and metallicity, the supernovae (SNe) of type Ib,c and II with mildly relativistic jets have been associated to core collapse of massive stars leading to supernovae (Hjorth & et al. 2003; Stanek & et al. 2003). Many authors (Barniol Duran, Bošnjak & Kumar 2012; Fraija, González & Lee 2012; Sacalui et al. 2012; Kumar & Barniol Duran 2010; Shen, Kumar & Piran 2010) have estimated these parameters to be $\epsilon_e \approx 0.1$, and $0.1 \leq \epsilon_B \leq 10^{-4}$, to obtain a good description of more than a dozen of GRBs.

Supernovae of type II and Ib are thought to have a radius of $R_s \approx 3 \times 10^{11}$ cm. Recently, IceCube reported the detection of two neutrino-induced events with energies between 1 - 10 PeV (IceCube Collaboration et al. 2013a). These events have been discussed as having an extragalactic origin, for instance; GRBs (Cholis & Hooper 2012) and low-luminosity GRBs (Liu & Wang 2013). On the other hand, high-energy neutrinos are produced in the decay of charged pions and muons when energetic protons in the jet interact with synchrotron thermalized photons or nucleons/mesons (pp, pn)/($\pi$, K) in the shocks. For internal shocks, synchrotron radiation and the number density of particles could be calculated with enough accuracy if we know the distribution of the magnetic field and the particle momentum in the shocked region. These quantities are calculated using the energy equipartition hypothesis through the equipartition parameters; electron equipartition ($\epsilon_e = U_e/U$) and magnetic equipartition ($\epsilon_B = U_B/U$) (Meszaros, Rees & Wieters 1998). Many authors (Barniol Duran, Bošnjak & Kumar 2012; Fraija, González & Lee 2012; Sacalui et al. 2012; Kumar & Barniol Duran 2010; Shen, Kumar & Piran 2010) have estimated these parameters to be $\epsilon_e \approx 0.1$, and $0.1 \leq \epsilon_B \leq 10^{-4}$, to obtain a good description of more than a dozen of GRBs.

On the other hand, the neutrino flavor ratio is expected to be, at the source, $\phi_{\nu_e}^0 : \phi_{\nu_\mu}^0 : \phi_{\nu_\tau}^0 = 1 : 2 : 0$ and on Earth (due to neutrino oscillations between the source and Earth) $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : \approx 1.1 GeV, neu-

* E-mail:nifrja@astro.unam.mx. Luc Binette-Fundación UNAM Fellow.
1 and $\phi_{\nu}^0 : \phi_{\bar{\nu}}^0 : \phi_{\nu}^e = 1 : 1.8 : 1.8$ for neutrino energies less and greater than 100 TeV, respectively, for gamma ray bursts ($\phi_{\nu}^0$ is the sum of $\nu$ and $\bar{\nu}$) [Kashti & Waxman 2005]. Also it has been pointed out that measurements of the deviation of the standard flavor ratio of astrophysical high-energy neutrinos may probe new physics [Learned & Pakvasa 1995; Athar, Jezabek & Yasuda 2004; Kashti & Waxman 2005]. As it is known, neutrino properties get modified when it propagates in a medium. Depending on their flavor, neutrinos interact via neutral and/or charged currents, for instance, $\nu_e$ interacts with electrons via both neutral and charged currents, whereas $\nu_{\mu} (\nu_{\tau})$ interacts only via the neutral current. This induces a coherent effect in which maximal conversion of $\nu_{\mu}$ as the Mikheyev-Smirnov-Wolfenstein effect (Wolfenstein 1978).

In this paper we both show that PeV neutrinos can be produced in hidden jets and estimate the flavor ratio of high-energy neutrinos expected on Earth. Firstly, we compute the energy range of neutrinos produced by cooling down of hadrons and mesons accelerated in a mildly relativistic jet. After that we take different matter density profiles to show that neutrinos may oscillate resonantly depending on the neutrino energy and mixing neutrino parameters. Finally, we discuss our results in the fail jet framework.

2 JET DYNAMICS

For the internal shocks, we consider a mildly relativistic shock propagating with bulk Lorentz factor $\Gamma_b = 10^{0.5} \Gamma_{b,0.5}$. Behind the shock, the comoving number density of particles and density of energy are $n'_e = n'_p = 1/(8 \pi m_p c^5) \Gamma_b^{-4} E_j \Gamma_b^{3} t_v,0^{3/2} = 3.1 \times 10^{18} \text{ cm}^{-3} t_v,0^{3/2}$ and $n'_p m_p c^2$, respectively, where we have taken the set of typical values for which the jet drifts but hardly breaks through the stellar envelope: the jet kinetic energy $E_j = 10^{41.5} E_{j,41.5}$ erg, the variability time scale of the central object $t_v = t_v,0$ with $t_v,0 = 0.1$ and 0.01, and the jet duration $t_j = 10 t_j,0$ [Razzaque, Mészáros & Waxman 2003; Ando & Beacom 2003; MacLachlan et al. 2013]. We assume that electrons and protons are accelerated in the internal shocks to a power-law distribution $N(\gamma) \propto \gamma^{-p} \tau^{p} \gamma^{p}$. The internal shocks due to shell collisions take place at a radius $r_j = 2 \Gamma_j^2 c t_v = 6 \times 10^{11} \text{ cm} \Gamma_j^2 t_v,0$. Electrons, with minimum energy $E_{e,min} = \frac{c}{2 \pi e} \Gamma_b^{3} m_e c^2 \Gamma_b$ and maximum energy limited by the dynamic time scale $t_{dyn} \simeq t_v \Gamma_b$, cool down rapidly by synchrotron radiation in the presence of the magnetic field given by

$$B' = \left( \frac{c \beta B}{c^2} \Gamma_b^{-4} E_j \nu_v^{-2} t_j^{-1} \right)^{1/2},$$

where $\beta = B^2 / (8 \pi m_e c^4)$ [Wolfenstein 1978].

The radiated photon energy by electron synchrotron emission with energy $E_{e}\gamma = \beta B' (h m_e c^2) E_{e}$, and also the opacity to Thomson scattering by these photons is

$$\tau'_{th} = \frac{\sigma_T}{4 \pi m_e c^2} \nu_v^{-3} E_j \nu_v^{-1} t_j^{-1}$$

$$= 3.9 \times 10^{9} \Gamma_{b,0.5}^{-3} E_{j,41.5} \nu_v^{-1} t_j^{-1} \nu_s^{-1}.\quad(2)$$

Due to the large Thomson optical depth, synchrotron photons will thermalize to a black body temperature, therefore the peak energy is given by

$$E_{\nu} \sim k_B T_{\nu} = \left( \frac{15 (h c)^3}{8 \pi^4 c^4} \right)^{1/4} \nu_v^{1/4} E_j^{1/4} \Gamma_b^{-1} \nu_v^{-1/4} t_j^{-1/4}$$

$$= 1.36 \text{ keV} E_{j,41.5}^{1/4} \Gamma_b^{-1/2} \nu_v^{-1/4} t_j^{-1/4} \nu_s^{-1/2}.\quad(3)$$

and the number density of thermalized photons is

$$n_{\gamma} \sim \left( \frac{15 (h c)^3}{8 \pi^4 c^4} \right)^{3/4} \nu_v^{-3/4} E_{j,41.5}^{3/4} \Gamma_b^{-3/2} \nu_v^{-3/4} t_j^{-3/4} \nu_s^{-1/4}.\quad(4)$$

Although keV photons can hardly escape due to the high optical depth, they are able to interact with relativistic protons accelerated in the jet, producing high-energy neutrinos via charged pion decay. The pion energies depend on the proton energy and characteristics of the jet.

3 HADRONIC MODEL

Protons accelerated in internal shocks, on the one hand, radiate photons by synchrotron radiation and also scatter the photons by inverse Compton (IC) scattering, and on the other hand, interact with thermal keV photons and hadrons by $p\gamma$ and $p$-hadron interactions. The optical depths for $p\gamma$ and $p$-hadron interactions are

$$\tau'_{p\gamma} = \frac{4 \zeta (3) \sigma_{p\gamma}}{\pi^2 (c h)^2} \left( \frac{15 (h c)^3}{8 \pi^4 c^4} \right)^{3/4} E_j \Gamma_b^{-3} \nu_v^{-1} t_j^{-1}$$

$$= 3.19 \times 10^{6} E_{j,41.5}^{3/4} \Gamma_b^{-3/2} \nu_v^{-3/4} t_j^{-3/4} \nu_s^{-1/4},\quad(5)$$

and

$$\tau'_{pp} = \frac{\sigma_{pp}}{4 \pi m_p c^5} E_j \Gamma_b^{-3} \nu_v^{-1} t_j^{-1}$$

$$= 1.77 \times 10^7 E_{j,41.5} \Gamma_b^{3} \nu_v^{-3/4} t_j^{-1} \nu_s^{-1/4}.\quad(6)$$

respectively. Due to the optical depths for $p\gamma$ and $p$-hadron interactions are very high, $p\gamma$ and $p$-hadron are effective, although $p$-hadron interactions are more effective at lower energy than $p\gamma$ interactions [Razzaque, Mészáros & Waxman 2004].

3.1 Cooling time scales

The shock acceleration time for an energy proton, $t'_{acc}$, is

$$t'_{acc} = \frac{2 \pi \xi}{c} r_L = \frac{2 \pi \xi^2}{c^2} B'_{\nu_v} \nu_v^{-1/2} \Gamma_b^{-1/2} \nu_v^{-1/2} t_j^{-1}$$

$$= \frac{3.19 \times 10^{6}}{2.04 \times 10^{12}} E_{j,41.5} \nu_v^{-1/2} \Gamma_b^{3/2} \nu_v^{-1/2} t_j^{-1/2} \nu_s^{-1/2}.\quad(7)$$

where $r_L$ is the Larmor’s radius and $\xi$ is a factor of equality. The acceleration time, $t'_{acc}$, gives an account of the maximum proton
energy achieved, when it is compared with the maximum cooling time scales. In the following subsections we are going to calculate the cooling time scales for protons and mesons.

### 3.1.1 Proton cooling time scales

The cooling time scale for proton synchrotron radiation is

$$t'_{p,syn} = \frac{E'_p}{\left(\frac{dE'_p}{dt}\right)_{syn}} = \frac{6\pi m^2 p c^6}{\sigma_T \beta^2 m^2 E'_p} E^{-1}_p \Gamma^0_b t^2_j \tau_e^{-1}$$

$$= 3.83 \times 10^{-5} E^{-2}_p E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1}$$

Protons in the shock region can upscatter the thermal keV photons $E'_\gamma$, with peak energy and density given in eqs. [3] and [4]. The IC cooling time scale in the Thomson regime is

$$t'^{th}_{p,IC} = \frac{E'_p}{\left(\frac{dE'_p}{dt}\right)_{th}^{IC}} = \frac{m^4 p c^8 \pi^2 (e/h) \left(\frac{E'_p}{(m_p c)^2}\right)^2}{5 \sigma_T \beta^2 m^2 \zeta(3) E'_p} E^{-1}_p \Gamma^0_b t^2_j \tau_e^{-1}$$

$$= 0.15 \times 10^{-10} E^{-2}_p E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1}$$

Also, the IC cooling time scale in the Klein-Nishina (KN) regime, $t'^{KN}_{p,IC} = \frac{E'_p}{\left(\frac{dE'_p}{dt}\right)_{IC}^{KN}} = \frac{3\pi^3 (e/h) E'_p E^{-1/2}_p E^{-1/2}_\gamma \Gamma^0_b t^2_j \tau_e^{-1/2}}{2\sqrt{30}\zeta(3) E'_p}$$

$$= 5.15 \times 10^{-10} E^{-2}_p E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1/2}$$

On the other hand, protons can upscatter thermal photons according to Bethe-Heitler (BH) process. The proton energy loss is taken away by the pairs produced in this process. The cooling time scale for the BH scattering is

$$t'_{BH} = \frac{E'_p}{\left(\frac{dE'_p}{dt}\right)_{BH}} = \frac{E'_p}{\left(\frac{dE'_p}{dt}\right)_{BH}} = \frac{n_{\gamma} \sigma_{BH} \Delta E_p}{\pi m^2 c^6 \sigma_{BH} (E'_p + E'_\gamma)}$$

$$= \frac{3\pi^3 (e/h) E'_p E^{-1/2}_p E^{-1/2}_\gamma \Gamma^0_b t^2_j \tau_e^{-1/2}}{2\sqrt{30}\zeta(3) E'_p}$$

where $\sigma_{BH} = \frac{\alpha^2}{4} ((2\pi/9)n)(2E'_\gamma E'_p (m_p c)^2((m_p c)^2) - 106/9)$. The energy loss rate due to pion production for $p\gamma$ interactions is $\sigma_{p\gamma} = \frac{\alpha^2}{4} ((2\pi/9)n)(2E'_\gamma E'_p (m_p c)^2((m_p c)^2) - 106/9)$.

For p-hadron interactions, $t'_{p,p} = \frac{10 \pi m^4 p c^4 E^{-1}_j \Gamma^0_b t^2_j}{\sigma_{pp}}$$

$$= 4.47 \times 10^{-4} E^{-2}_j E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1}$$

In figs. [1] and [2] we have plotted the proton cooling time scales when internal shocks take at $r = 6 \times 10^8$ cm and $r = 6 \times 10^{10}$ cm, respectively.

### 3.1.2 Meson cooling time scales

High-energy charged pions and kaons produced by p-hadron and $p\gamma$ interactions ($p+/p- \rightarrow X + \pi^+/K^\pm$) radiate in the presence of the magnetic field (eq. [1]). Therefore, their cooling time scales are

$$t'_{\pi^+,syn} = \frac{E'_{\pi^+}}{\left(\frac{dE'_{\pi^+}}{dt}\right)} \simeq \frac{6\pi m^6 p^4 c^6}{\sigma_T \beta^2 m^2} E^{-1}_B E^{-1}_j \Gamma^0_b t^2_j \tau_e^{-1}$$

$$= 1.9 \times 10^{-2} E^{-1}_B E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1}$$

and

$$t'_{K^+,syn} = \frac{E'_{K^+}}{\left(\frac{dE'_{K^+}}{dt}\right)} \simeq \frac{6\pi m^6 p^4 c^6}{\sigma_T \beta^2 m^2} E^{-1}_B E^{-1}_j \Gamma^0_b t^2_j \tau_e^{-1}$$

$$= 2.94 \times 10^{-2} E^{-1}_B E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1}$$

As protons can collide with secondary pions and kaons ($\pi^+/p + K^+/p$), then its respective cooling time scale is given by

$$t'_{had} = \frac{10 \pi m^4 p c^4 E^{-1}_j \Gamma^0_b t^2_j}{\sigma_{(pK/p+\gamma)}}$$

$$= 5.47 \times 10^{-5} E^{-1}_B E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1}$$

Here we have used the cross-section $\sigma_{(pK/p+\gamma)} \approx 3 \times 10^{-26}$ cm$^2$. Because the mean lifetime of these mesons may be comparable with the synchrotron and hadron time scales in some energy range, it is necessary to consider the cooling time scales related to their mean lifetime which are given by

$$t'_{\pi^+,dec} = \frac{E'_{\pi^+}}{m_{\pi c^2} \tau_{\pi^+}}$$

$$= 1.87 \times 10^{-5} E^{-1}_B E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1}$$

and

$$t'_{K^+,dec} = \frac{E'_{K^+}}{m_{K^+ c^2} \tau_{K^+}}$$

$$= 2.51 \times 10^{-8} E^{-1}_B E^{-1}_{\gamma,5.1,5} \Gamma^0_b t^2_j \tau_e^{-1}$$

where $\tau_{\pi^+ / K^+}$ is the mean lifetime for $\pi^+ / K^+$ and $E_{\pi^+ / K^+} = 10^9 E_{\gamma} + K^+ eV$.

In figs. [3] and [4], we have plotted the meson cooling time scales when internal shocks take at $r = 6 \times 10^9$ cm and $r = 6 \times 10^{10}$ cm and the magnetic equipartition parameter is in the range $0.1 \leq \epsilon_B \leq 10^{-4}$.

### 3.2 Neutrino production

The single-pion production channels are $p + \gamma \rightarrow n + \pi^+$ and $p + \gamma \rightarrow p + \pi^0$, where the relevant pion decay chains are $\pi^0 \rightarrow 2\gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e$, $\nu_\mu \rightarrow \nu_\mu \rightarrow e^+ + \nu_e$, $\nu_\mu \rightarrow e^+ + \nu_e$, $\nu_\mu \rightarrow e^+ + \nu_e$ (Dermer & Atwood 2003), then the threshold neutrino energy from $p\gamma$ interaction is

$$E_{\nu,\pi} = 2.5 \times 10^{-5} \left(\frac{8\pi^4 t^4_j}{15h}\right)^{1/4} (m^2_{\Delta} - m^2_p) / (1 - \cos \theta)$$

$$= 9.72 \text{ TeV} E^{-1/4}_{\gamma,5.1,5} t^{-1/4}_j \epsilon_{\nu,5/14}^{-1/4} \epsilon_{\gamma,5/14}^{-1/4}$$

Comparing the time cooling scales we can estimate the neutrino break energy for each process. Equaling $t_{had} \simeq t'_{p,\gamma,syn}$, we can approximately estimate the maximum proton energy

$$E'_{p,max} = \left(\frac{3 \pi m^6 p^4 c^{11/2}}{\sigma_T \zeta^2 \beta^2 m^2} \right)^{1/2} E^{-1/4}_B E^{-1/4}_j \Gamma^0_b t^2_j \tau_e^{-1}$$

$$= 4.3 \times 10^8 \text{ GeV} E^{-1/4}_{\gamma,5.1,5} t^{-1/4}_j \epsilon_{\gamma,5/14}^{-1/4} \epsilon_{\nu,5/14}^{-1/4}$$

From the condition of the synchrotron cooling time scales for mesons ($t'_{\pi^+,syn} = t'_{had}$ and $t'_{K^+,syn} = t'_{had}$), one may roughly define the neutrino break energies as

$$E_{\nu,\pi,syn} = 0.15 \times \frac{m^4_p c^6 \sigma_{pp}^{-1}}{m_p \sigma_T \beta^2 m^2}$$

$$= 10.5 \text{ GeV} \epsilon_{\nu,5/14}$$

© 0000 RAS, MNRAS 000, 000–000
4 N. Fraija

and

\[ E_{\nu, k+\text{syn}}^s = 0.3 \times \frac{m_\mu^4 c^2 \sigma_{pp}}{m_\mu \sigma_{\mu \pi^0}^2 m_2^2} t^{-1} \]

\[ = 3.28 \text{TeV} \tau_B^{-1}. \]  

(22)

From the lifetime condition of cooling time scale (\( t_{\nu, \text{dec}}^s = t_{\text{had}}^s \)) and \( t_{\nu, \text{dec}}^s = t_{\text{had}}^s \), one again we can obtain the neutrino break energies, which for these cases are

\[ E_{\nu, \pi^+ \ell t} = 2.5 \frac{\pi m_\mu m_\pi^0}{\rho_{\ell}} \frac{E_j}{\tau_{\pi^0}} \Gamma_{b, 0.5} \frac{t_\ell^2}{t_j} \]

\[ = 0.6 \text{TeV} \frac{E_j}{\tau_{\pi^0}} \Gamma_{b, 0.5} \frac{t_\ell^2}{t_j}. \]  

(23)

and

\[ E_{\nu, \pi^+ \ell t} = 5 \frac{m_\mu m_\pi^0}{\rho_{\ell}} \frac{E_j}{\tau_{\pi^0}} \Gamma_{b, 0.5} \frac{t_\ell^2}{t_j} \]

\[ = 8.92 \text{TeV} \frac{E_j}{\tau_{\pi^0}} \Gamma_{b, 0.5} \frac{t_\ell^2}{t_j}. \]  

(24)

It is important to say that muons may be suppressed by electromagnetic energy losses and in that case would not contribute much to high-energy neutrino production. The ratio \( t_{\pi^+ / K^+ \text{cool}}^s / t_{\pi^+ / K^+ \text{dec}}^s \) determines the suppression of mesons before they decay to neutrinos (Razzaque, Mészáros & Waxman 2005).

In fig. 5 we have plotted the neutrino creation by direct interaction processes at different distances, \( 6 \times 10^3 \text{ cm} \) (above) and \( 6 \times 10^{10} \text{ cm} \) (below), as a function of the magnetic equipartition parameter.

4 DENSITY PROFILE OF THE SOURCE

Analytical and numerical models of density distribution in a presupernova have shown a strong dependence on radius \( r \propto r^{-n} \), with \( n=3/2 \) - 3 above the core, being \( 3/2 \) and 3 convective and radiative envelopes respectively (Woosley, Langer & Weaver 1995, Shigeyama & Nomoto 1990, Arnett 1991). In particular, distributions with \( \rho \propto r^{-3} \) and \( \rho \propto r^{-17/7} \) have been proposed to describe simple blast wave distributions (Bethe & Pizzocher 1989). Following Mena, Mocioiu & Razzaque (2007), we use three models of density profile; Model [A], Model [B] and Model [C].

Model [A],

\[ [A] \rho(r) = 4.0 \times 10^{-6} \left( \frac{R_c}{r} \right)^{-3} \text{ g cm}^{-3}, \]  

(25)

corresponds to a polytropic hydrogen envelope with \( \rho(r) \propto r^{-3} \), scaling valid in the range \( r_{jet} \propto r \geq R_c \). Model [B],

\[ [B] \rho(r) = 3.4 \times 10^{-5} \text{ g cm}^{-3} \times \begin{cases} \left( \frac{R_c}{r} \right)^{17/7}; & 10^{10.8} \text{ cm} < r < r_0 = 10^{12} \text{ cm} \\ \left( R_c/5 \right)^{17/7}/(r - R_c); & r > r_0, \end{cases} \]  

(26)

is a power-law fit with an effective polytropic index \( n_{eff} = 17/7 \) as done for SN 1987A (Chevalier & Soker 1989). Here \( r_j \sim 1 \times 10^{10.8} \text{ cm} \) is the radius of inner border of the envelope, where the density \( \rho = 0.4 \text{ g cm}^{-3} \). Associating the number of electron per nucleon \( Y_e = 0.5 \), we obtained the number density of electrons as \( N_e = N_0 \rho(r) Y_e = 1.2 \times 10^{23} \text{ cm}^{-3} \) and Model [C],

\[ [C] \rho(r) = 6.3 \times 10^{-6} \left( \frac{R_c}{r} \right)^{-3} \text{ g cm}^{-3} \]

\( (n_{eff}, A) = \left\{ \begin{array} \{ (2.1, 20); & 10^{10.8} \text{ cm} < r < 10^{11} \text{ cm}, \\ (2.5, 1); & r > 10^{11} \text{ cm} \end{array} \right\} \]

includes a sharp drop in density at the edge of the helium core (Matzner & McKee 1999).

5 NEUTRINO MIXING

In the following subsections we are going to describe the neutrino oscillations in the matter (along the jet for three density profiles given in section 4) and in vacuum (its path up to Earth). We will be using the best fit parameters for two-neutrino mixing (solar, atmospheric and accelerator neutrino experiments) and three-neutrino mixing. The best fit value of solar, atmospheric and accelerator neutrino experiments are given as follows.

Solar Neutrinos are electron neutrinos produced in the thermonuclear reactions which generate the solar energy. The Sudbury Neutrino Observatory (SNO) was designed to measure the flux of neutrinos produced by \(^7\)B decays in the sun, so-called \(^7\)B neutrinos, and to study neutrino oscillations, as proposed by Chen (1985). A two-flavor neutrino oscillation analysis gave the following parameters: \( \Delta m^2 = (5.6_{-0.6}^{+1.4}) \times 10^{-5} \text{ eV}^2 \) and \( \tan^2 \theta = 0.427_{-0.029}^{+0.01} \) (Aharmim & et al. [2011]).

Atmospheric Neutrinos are electron neutrinos \( \nu_e \) produced mainly from the decay chain \( \pi \to \mu + \nu_\mu \) followed by \( \mu \to e + \nu_e + \nu_\nu \). Super-Kamiokande (SK) observatory observes interactions between neutrinos with electrons or with nuclei or water via the water Cherenkov method. Under a two-flavor disappearance model with separate mixing parameters between neutrinos and antineutrinos there were found the following parameters for the SK-I + II + III data: \( \Delta m^2 = (2.4_{-0.4}^{+0.7}) \times 10^{-3} \text{ eV}^2 \) and \( \sin^2 2\theta = 1.0_{-0.0}^{+0.0} \) (Abe & et al. [2011]).

Reactor Neutrinos are produced in Nuclear reactors. Kamioka Liquid Scintillator Anti-Neutrino Detector (KamLAND) was initially designed to detect reactor neutrinos and so later it was prepared to measure \(^7\)Be solar neutrinos. A two neutrino oscillation analysis gives \( \Delta m^2 = (7.9_{-0.6}^{+0.5}) \times 10^{-5} \text{ eV}^2 \) and \( \tan^2 \theta = 0.4_{-0.0}^{+0.0} \) (Araki & et al. [2003]). Shirai & KamLAND Collaboration 2007, the KamLAND Collaboration & Mitsui 2011.

Accelerator Neutrinos are mostly produced by \( \pi \) decays (and some K decays), with the pions produced by the scattering of the accelerated protons on a fixed target. The beam can contain both \( \mu \)- and e-neutrinos and antineutrinos. There are two categories: Long and short baselines.

Long-baseline experiments with accelerator beams run with a baseline of about a hundred of kilometers. K2K experiment was designed to measure neutrino oscillations using a man-made beam with well controlled systematics, complementing and confirming the measurement made with atmospheric neutrinos. \( \Delta m^2 = (2.8_{-0.7}^{+0.3}) \times 10^{-3} \text{ eV}^2 \) and \( \sin^2 2\theta = 1.0 \) (Ahn & et al. 2006).

Short-baseline experiments with accelerator beams run with a baseline of about hundreds of meters. Liquid Scintillator Neutrino Detector (LSND) was designed to search for \( \nu_\mu \to \nu_\ell \) oscillations using \( \nu_\mu \) from \( \pi^+ \) decay in flight (Athanassopoulos & et al. [1996, 1998]). The region of parameter space has been partly tested by Karlsruhe Rutherford medium energy neutrino KARMEN (Armbruster & et al. 2002) and MiniBooNe experiments (Church & et al. 2002) found two well-defined regions of oscillation

\[ 3 \text{ this value was obtained using a global analysis of data from KamLAND and solar-neutrino experiments} \]
parameters with either $\delta m^2 \approx 7$ eV$^2$ or $\delta m^2 < 1$ eV$^2$ compatible with both LAND and KARMEN experiments, for the complementary condition. The MiniBooNE experiment was specially designed to verify the LSND’s neutrino data. It is currently running at Fermilab and is searching for $\nu_e (\bar{\nu}_e)$ appearance in a $\nu_\mu (\bar{\nu}_\mu)$ beam. Although MiniBooNE found no evidence for an excess of $\nu_e$ candidate events above 475 MeV in the $\nu_\mu \rightarrow \nu_e$ study, there was observed a $3.0 \sigma$ excess of electron-like events below 475 MeV (Aguilar-Arevalo et al. 2009, 2010, 2007). In addition, in the $\nu_\mu \rightarrow \nu_e$ study, MiniBooNE found evidence of oscillations in the 0.1 to 1.0 eV$^2$, which are consistent with LSND results (Athanassopoulos et al. 1996, 1998).

Combining solar, atmospheric, reactor and accelerator parameters, the best fit values of the three neutrino mixing are

\[ \sin^2 \theta_{12} = 0.446^{+0.030}_{-0.029}, \]  
\[ \sin^2 \theta_{13} = 0.04; \]  
\[ \sin^2 \theta_{23} = 0.50^{+0.003}_{-0.003}. \]

In this subsection, we will consider the neutrino oscillation process

\[ \nu_e \leftrightarrow \nu_\mu. \]  

The evolution equation for the propagation of neutrinos in the above medium is given by

\[ i \frac{d}{dt} \left( \begin{array}{c} \nu_e \\ \nu_\mu \end{array} \right) = \left( \begin{array}{cc} V_{eff} - \Delta \cos 2\theta & \frac{\Delta}{2} \sin 2\theta \\ \frac{\Delta}{2} \sin 2\theta & 0 \end{array} \right) \left( \begin{array}{c} \nu_e \\ \nu_\mu \end{array} \right), \]

where $\Delta = \delta m^2 / 2E_{\nu}$, $V_{eff} = \sqrt{3}G_F N_e$ is the effective potential, $E_{\nu}$ is the neutrino energy, and $\theta$ is the neutrino mixing angle. For anti-neutrinos one has to replace $N_e$ by $-N_e$. The conversion probability for a given time $t$ is

\[ P_{\nu_e \rightarrow \nu_\mu (\nu_\mu \rightarrow \nu_e)}(t) = \frac{\Delta^2 \sin^2 \theta}{\omega^2} \sin^2 \left( \frac{\omega t}{2} \right), \]

with

\[ \omega = \sqrt{(V_{eff} - \Delta \cos 2\theta)^2 + \Delta^2 \sin^2 2\theta}. \]

The oscillation length for the neutrino is given by

\[ L_{osc} = \frac{L_0}{\sqrt{\cos^2 2\theta (1 - \frac{V_{eff}}{\Delta \cos 2\theta})^2 + \sin^2 2\theta}}, \]

where $L_0 = 2\pi / \Delta$ is the vacuum oscillation length. If the density of the medium is such that the condition $\sqrt{3}G_F N_e = \Delta \cos 2\theta$ is satisfied, the resonant condition,

\[ V_{eff} = \Delta \cos 2\theta, \]

can come about, therefore the resonance length can be written as

\[ L_{res} = \frac{L_0}{\sin 2\theta}. \]

Combining eqs (33) and (34) we can obtain the resonance density as a function of resonance length

\[ \rho_R = \left[ \begin{array}{c} \frac{3.69 \times 10^{-4}}{E_{\nu,T} \gamma} \\ \frac{1.39 \times 10^{-2}}{E_{\nu,T} \gamma} \end{array} \right] \left[ \begin{array}{c} 1 - \frac{E_{\nu,T}^2}{1.8 \times 10^{11} \text{ cm}^3 / \gamma} \\ 1 - \frac{E_{\nu,T}^2}{1.8 \times 10^{11} \text{ cm}^3 / \gamma} \end{array} \right] \left( \begin{array}{c} \text{sol}, \\ \text{atmos}, \end{array} \right) \]

where sol, atmos. and accel. correspond to solar, atmospheric and accelerator parameters.

In addition of the resonance condition, the dynamics of this transition must be determined by adiabatic conversion through the adiabaticity parameter

\[ \gamma = \frac{\Delta m^2}{2E_{\nu}} \sin 2\theta \tan 2\theta \left| \frac{1}{\rho} \frac{d\rho}{d\theta} \right|, \]

with $\gamma \gg 1$ or the flip probability given by

\[ P_f = e^{-2\gamma}, \]

where $\rho$ is given by eqs. (33), (34) and (35).

### 5.1 Neutrino oscillation inside the jet

When neutrino oscillations take place in the matter, a resonance could occur that dramatically enhances the flavor mixing and can lead to maximal conversion from one neutrino flavor to another. This resonance depends on the effective potential, density profile of the medium, and oscillation parameters. As $\nu_e$ is the one that can interact via CC, the effective potential can be obtained calculating the difference between the potential due to CC and NC contributions (Kuo & Pantaleone 1989).

#### 5.1.1 Two-Neutrino Mixing

In this subsection, we will consider the neutrino oscillation process $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$. The evolution equation for the propagation of neutrinos in the above medium is given by

\[ i \frac{d}{dt} \left( \begin{array}{c} \nu_e \\ \nu_\mu \end{array} \right) = \left( \begin{array}{cc} V_{eff} - \Delta \cos 2\theta & \frac{\Delta}{2} \sin 2\theta \\ \frac{\Delta}{2} \sin 2\theta & 0 \end{array} \right) \left( \begin{array}{c} \nu_e \\ \nu_\mu \end{array} \right), \]

with

\[ \omega = \sqrt{(V_{eff} - \Delta \cos 2\theta)^2 + \Delta^2 \sin^2 2\theta}. \]

The oscillation length for the neutrino is given by

\[ L_{osc} = \frac{L_0}{\sqrt{\cos^2 2\theta (1 - \frac{V_{eff}}{\Delta \cos 2\theta})^2 + \sin^2 2\theta}}, \]

where $L_0 = 2\pi / \Delta$ is the vacuum oscillation length. If the density of the medium is such that the condition $\sqrt{3}G_F N_e = \Delta \cos 2\theta$ is satisfied, the resonant condition,

\[ V_{eff} = \Delta \cos 2\theta, \]

can come about, therefore the resonance length can be written as

\[ L_{res} = \frac{L_0}{\sin 2\theta}. \]
6  N. Fraija

\[
\sin 2\theta_{13, m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} - 2E_{\nu}V_{e}/\delta m_{32}^2)^2 + (\sin 2\theta_{13})^2}} \quad (45)
\]

and

\[
S_{ij} = \sin^2 \left( \frac{\Delta \mu_{ij}^2}{4E_{\nu}} \right). \quad (46)
\]

Here $\Delta \mu_{ij}^2$ are given by

\[
\begin{align*}
\Delta \mu_{21}^2 &= \frac{\Delta m_{32}^2}{2} \left( \frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} - 1 \right) - E_{\nu}V_{e}, \\
\Delta \mu_{32}^2 &= \frac{\Delta m_{32}^2}{2} \left( \frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} + 1 \right) + E_{\nu}V_{e}, \\
\Delta \mu_{31}^2 &= \Delta m_{32}^2 \frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}},
\end{align*}
\]

where

\[
\begin{align*}
\sin^2 \theta_{13,m} &= \frac{1}{2} \left( 1 - \sqrt{1 - \sin^2 2\theta_{13,m}} \right), \\
\cos^2 \theta_{13,m} &= \frac{1}{2} \left( 1 + \sqrt{1 - \sin^2 2\theta_{13,m}} \right). \quad (48)
\end{align*}
\]

The oscillation length for the neutrino is given by

\[
L_{osc} = \frac{L_{\nu}}{\sqrt{\cos^2 2\theta_{13} \left( 1 - \frac{\Delta m_{32}^2 V_{e}}{\sin^2 2\theta_{13,m}} \right)^2 + \sin^2 2\theta_{13,m}}} \quad (49)
\]

where $L_{\nu} = 4\pi E_{\nu}/\Delta m_{32}^2$ is the vacuum oscillation length. From the resonance condition, $\sqrt{2G_F} N_e = \Delta \cos 2\theta_{13}$, the resonance length and density are related as

\[
\rho_R = \frac{1.9 \times 10^{-2}}{E_{\nu, TeV}} \left[ 1 - E_{\nu, TeV} \left( 8.2 \times 10^{10} \text{cm}/L_{\nu} \right) \right]^{-1/2} \text{gr/cm}^3. \quad (50)
\]

On the other hand, generalizing the adiabaticity parameter, $\gamma$, to three-mixing neutrinos, it can be written as

\[
\gamma \equiv \frac{\delta m_{32}^2}{2E} \sin 2\theta_{13} \tan 2\theta_{13} \left| \frac{d}{dR} \right|_{\nu}, \quad (51)
\]

with the flip probability given by eq. (38).

5.2 Neutrino Oscillation from Source to Earth

Between the surface of the star and the Earth the flavor ratio $\phi_{\nu_e}^{\nu_e} : \phi_{\nu_\mu}^{\nu_\mu} : \phi_{\nu_\tau}^{\nu_\tau}$ is affected by the full three description flavor mixing, which is calculated as follows. The probability for a neutrino to oscillate from a flavor state $\alpha$ to a flavor state $\beta$ in a time starting from the emission of neutrino at time $t=0$, is given as

\[
P_{\nu_\alpha \rightarrow \nu_\beta} = \left|< \nu_\beta | \nu_\alpha(t = 0) > \right|^2 = \delta_{\alpha\beta} - 4 \sum_{j>3} U_{e\alpha} U_{\beta i} U_{e\gamma} U_{\gamma j} \sin^2 \left( \frac{\delta m_{ij}^2 L}{4E_{\nu}} \right). \quad (52)
\]

Using the set of parameters give in eq. (29), we can write the mixing matrix

\[
U = \begin{pmatrix} 0.816669 & 0.544650 & 0.190809 \\ -0.504583 & 0.513419 & 0.694115 \\ 0.280805 & -0.663141 & 0.694115 \end{pmatrix}. \quad (53)
\]

Averaging the sin term in the probability to $\sim 0.5$ for larger distances $L$ [Learned & Pakvasa (1992)], the probability matrix for a neutrino flavor vector of $(\nu_e, \nu_\mu, \nu_\tau)_{\text{source}}$ changing to a flavor vector $(\nu_e, \nu_\mu, \nu_\tau)_{\text{Earth}}$ is given as

\[
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{\text{source}} = \begin{pmatrix} 0.534143 & 0.265544 & 0.200313 \\ 0.265544 & 0.366436 & 0.368020 \\ 0.200313 & 0.368020 & 0.431667 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{\text{Earth}}. \quad (54)
\]

for distances longer than the solar system.

6 RESULTS AND DISCUSSIONS

We have considered a core collapse of massive stars leading to supernovae (SNe) of type Ib,c and II with mildly relativistic jets. Although this mildly relativistic jet may not be able to break through the stellar envelope, electrons and protons are expected to be accelerated in the internal shocks, and then to be cooled down by synchrotron radiation, inverse Compton and hadronic processes ($\gamma$ and p-hadron/meson). Photons from electron synchrotron radiation thermalized to a some keV-peak energy serve as cooling mechanism for accelerated protons by means of $\gamma$ interactions. Another cooling mechanism of protons considered here are the p-p interactions, due to the high number density of protons ($3.1 \times 10^{52} \text{cm}^{-3} < n_p < 3.1 \times 10^{52} \text{cm}^{-3}$) [Razzaque, Mészáros & Waxman (2003)]. In $\gamma$ and p-p interactions, high-energy pions and kaons are created which in turn interact with protons by $\pi$-p and $K$-p interactions, producing another hadronic/meson cooling mechanism. To illustrate the degree and energy region of efficiency of each cooling process, we have plotted the proton (figures 1 and 2) and meson (figures 3 and 4) time scales when internal shocks take place at $6 \times 10^9$ cm and $6 \times 10^{10}$ cm and, the magnetic field lies in the range $3.4 \times 10^7 \text{G} < B' < 1.1 \times 10^8 \text{G}$. Comparing the time scales in figures 1 and 2, one can observe that the maximum proton energy is when the acceleration and synchrotron time scales are equal; it happens when proton energy is in the range $10^{15} \text{eV} < E_p < 10^{16} \text{eV}$ which corresponds to internal shocks at $6 \times 10^9$ cm with $B' = 1.1 \times 10^{10} \text{G}$ and $6 \times 10^{10}$ cm with $B' = 3.4 \times 10^8 \text{G}$, respectively. In figs. 3 and 4 one can see that hadronic time scales are equal to other time scales at different energies. For instance, internal shocks at $6 \times 10^9$ cm and $B' = 1.1 \times 10^9 \text{G}$, the time scales of pion synchrotron emission and hadronic are equal for pion energy $\sim 5 \times 10^3 \text{eV}$. Computing the break meson energies for which time scales are equal to each other, we can estimate the break neutrino energies. From the equality of kaon/pion lifetime and synchrotron cooling time scales we obtain the break neutrino energies $\sim (24/179) \text{GeV}$ and $\sim 428 \text{GeV}/69 \text{TeV}$, respectively. Also, considering $\gamma$ interactions the threshold neutrino energy $\sim 3 \text{TeV}$ is obtained. Taking into account the distances of internal shocks ($6 \times 10^9$ cm and $6 \times 10^{10}$ cm) we have plotted the neutrino energy as a function of the magnetic equipartition parameter in the range $0.1 \leq \epsilon_B \leq 10^{-4}$ ($3.4 \times 10^7 \text{G} < B' < 1.1 \times 10^{10} \text{G}$). As shown in the fig. 5 neutrino energy between 1 - 10 PeV can be generated for $\epsilon_B$ between $3.5 \times 10^{-3}$ and $4.1 \times 10^{-4}$, that corresponds to a magnetic field in the range $2.02 \times 10^9$ - $6.9 \times 10^8$ G at $6 \times 10^9$ cm and $6 \times 10^{10}$ cm from the central engine, respectively. Under this scenario, shocked jets are bright in high-energy neutrinos and dark in gamma rays.

On the other hand, taking into account the range of neutrino energy ($24 \text{GeV} < E_{\nu} < 69 \text{TeV}$), internal shocks at a distance of $6 \times 10^{10}$ cm, strength of magnetic field of $1.1 \times 10^{10} \text{G}$ and considering three models of density profile (see section III. eqs. 28 and 29) of a pre-supernova star, we present a full description of two- and three-flavor neutrino oscillations. Based on these models of density profiles we calculate the effective potential, the resonance condition and, the resonance length and density. From the
resonance condition, we obtain the resonance density ($\rho_R$) as a function of resonance length ($l_R$) for two (eq. 36) and three flavors (eq. 50). We overlap the plots of the density profiles as a function of distance with the resonance conditions (resonance density as a function of resonance length). They are shown in Fig 7 (two flavors) and in Fig. 8 (three flavors). For two flavors, we have taken of distance with the resonance conditions (resonance density as a function of resonance length) is less than the star radius for two flavors, the one that meets the resonance condition for all models of density profiles while neutrinos of energy 178 GeV meet marginally the resonance condition just for the model [B]. Neutrinos with other energy cannot meet the resonance condition. Using atmospheric parameters, the resonance length lies in the range $\sim (10^{11} - 10^{11.3}) \text{ cm}$ and the resonance density in $\sim (10^4 - 10^8) \text{ g/cm}^2$. As shown, neutrinos in the energy range of 178 GeV - 3 TeV can oscillate many times before leaving the source. Although the resonance length of neutrino with energy 24 GeV is smaller than star radius, the resonance density is greater than other models. Using accelerator parameters, the resonance length is less than $10^{10.2} \text{ cm}$ and the resonance density lies in the range $\sim (10^2 - 10^3) \text{ g/cm}^2$. Although the resonance length is smaller than the star radius for two flavors, the one that meets the resonance density is the neutrino energy 69 TeV. For three flavors, the range of resonance length is $\sim (10^9 - 10^{12.5}) \text{ cm}$ and resonance density is $\sim (0.9 - 10^{-4}) \text{ g/cm}^3$, presenting a similar behavior to that described by means of atmospheric parameters. As the dynamics of resonant transitions is not only determined by the resonance condition, but also by adiabatic conversion, we plot the flip probability as a function of neutrino energy for two (fig.8) and three flavors (fig.9). Dividing the plots of flip probabilities in three regions of less than 0.2, between 0.2 and 0.8 and greater than 0.8, we have that in the first case ($P_\gamma < 0.2$), a pure adiabatic conversion occurs, the last case ($P_\gamma > 0.8$) is a strong violation of adiabaticity and the intermediate region 0.2 < $P_\gamma < 0.8$ represents the transition region (Dighe & Smirnov 2000). In Fig 8 the top, middle and bottom plots are obtained using solar, atmospheric and accelerator parameters of neutrino oscillations, respectively. As shown in top figure, the pure adiabatic conversion occurs when neutrino energy is less than $5 \times 10^{11} \text{ eV}$ for model [A] and [C] and, $\sim 10^{12} \text{ eV}$ for model [B] and, the strong violation of adiabaticity is given for neutrino energy greater than $6 \times 10^{12} \text{ eV}$ in the three profiles. In the middle figure, one can see that independently of the profile, neutrinos with energy of less than $E_\nu=10^{14} \text{ eV}$ can have pure adiabatic conversions. In the bottom figure, the three models of density profiles have the same behavior for the whole energy range. Neutrinos with energy less than $\sim 10^{13.4} \text{ eV}$ and greater than $\sim 10^{13.8} \text{ eV}$ present conversion adiabatically pure and strong violation, respectively. In fig.2 the flip probability for three flavors are plotted. The energy range for each region of $P_\gamma$ changes marginally according to the model of density profile. Neutrinos with $E_\nu \sim 10^{12} \text{ eV}$ are capable of having pure adiabatic conversion in [B] but not in [A] or [C]. The strong violation of adiabaticity begins when the neutrino energies are $E_\nu \sim 10^{13} \text{ eV}$ and $E_\nu \sim 10^{13.8} \text{ eV}$ for [A] and [C], respectively.

On the other hand, we have also plotted (fig. 10) the oscillation probabilities for three flavors as a function of energy when neutrinos keep moving at a distance of $r=10^{11} \text{ cm}$ (above) and $r=10^{12} \text{ cm}$ (below) from the core. In the top figure, the survival probability of electron neutrino, $P_{\nu_e}$, is close to one regardless of neutrino energy, therefore the conversion probabilities $P_{\nu_\mu}$ and $P_{\nu_\tau}$ are close to zero, as shown. Depending on the neutrino energy, the survival probability of muon and tau neutrino, $P_{\nu_\mu}$ and $P_{\nu_\tau}$, oscillates between zero and one. For example, for $E\sim 430 \text{ GeV}$, the conversion probability of muon $P_{\nu_\mu}$ is close to zero while the survival probability of muon and tau neutrino, $P_{\nu_\mu}$ and $P_{\nu_\tau}$, are close to one, and for $E\sim 1 \text{ TeV}$ probabilities change dramatically, being $P_{\nu_\mu} \sim 1$ and $P_{\nu_\tau} P_{\nu_\mu} \sim 0$. In the bottom figure, neutrinos are moving along the jet at $r=10^{11} \text{ cm}$ and although the survival and conversion probabilities have similar behaviors to those moving to $r=10^{13} \text{ cm}$, they are changing faster. To have a better understanding, we have separated all probabilities and plotted them in fig.11. From up to down, the probabilities of electron neutrino and survival probability of muon neutrino are shown in the first and second graph, respectively, and the conversion and survival probability of tau neutrino are plotted in the third and fourth graph, respectively. Moreover, we have plotted in figs. 12 and 13 the oscillation probabilities as a function of distance, when neutrinos are produced at a radius $6 \times 10^{10} \text{ cm}$ and $6 \times 10^{10} \text{ cm}$, respectively, and continue to propagate along the jet.

We take into account four neutrino energies $E_\nu=178 \text{ GeV}$, $E_\nu=428 \text{ GeV}$, $E_\nu=3 \text{ TeV}$ and $E_\nu=69 \text{ TeV}$. As shown, as neutrino energy increases, the probabilities oscillate less. For instance, when an electron neutrino with energy $E_\nu=178 \text{ GeV}$ propagates along the jet, the survival probability of electron changes from one at $\sim 8 \times 10^{10} \text{ cm}$ to zero at $\sim 9.5 \times 10^{10} \text{ cm}$. For $E_\nu=428 \text{ GeV}$ (3 TeV), the survival probabilities change from one at $9.1 \times 10^{10} \text{ cm}$ to zero at $1.8 \times 10^{11} \text{ cm}$ and for $E_\nu=69 \text{ TeV}$, the probability is constant in this range (greater than $\sim 10^{12} \text{ cm}$). In the last case, neutrino does not oscillate to another flavor during its propagation. Finally, considering a flux ratio for $\tau$, $K$ and $\mu$ decay of 1:2:0, the density profile [A] and oscillation probabilities at three distances ($10^{11} \text{ cm}$, $10^{11.5} \text{ cm}$ and $10^{12} \text{ cm}$), we show in table 1 the flavor ratio on the surface of star. Also, computing the vacuum oscillation effects between the source and Earth (Eq. 51), we estimate and show in table 2 the flavor ratio expected on Earth when neutrinos emerge from the star at $L=(10^{11}, 10^{11.5} \text{ and } 10^{12}) \text{ cm}$.

| $E_\nu$ (TeV) | $P_{\nu_e}$ : $P_{\nu_\mu}$ : $P_{\nu_\tau}$ (L=10$^{11}$ cm) | $P_{\nu_e}$ : $P_{\nu_\mu}$ : $P_{\nu_\tau}$ (L=10$^{11.5}$ cm) | $P_{\nu_e}$ : $P_{\nu_\mu}$ : $P_{\nu_\tau}$ (L=10$^{12}$ cm) |
|----------------|---------------------------------|---------------------------------|---------------------------------|
| 0.024 | 0.946:1.949:0.115 | 0.697:1.405:0.899 | 0.881:1.578:0.541 |
| 0.178 | 0.510:1.814:0.676 | 0.987:1.386:0.627 | 0.507:1.807:0.686 |
| 0.428 | 0.983:1.589:0.428 | 0.659:1.871:0.524 | 0.538:1.721:0.741 |
| 3 | 0.896:1.212:0.892 | 0.502:1.753:0.744 | 0.501:1.762:0.737 |
| 68.5 | 0.999:1.997:0.003 | 0.998:1.972:0.030 | 0.979:1.746:0.275 |

7 SUMMARY AND CONCLUSIONS

We have done a wide description of production channels of high-energy neutrinos in a middle relativistic hidden jet and also shown that neutrinos with energies between 1 - 10 PeV can be generated. Taking into account a particular range of neutrino energies generated in the internal shocks at a distance of $6 \times 10^{10} \text{ cm}$ and with a distribution of magnetic field $1.1 \times 10^{10} \text{ G}$, we have shown their oscillations between flavors along the jet for three models of den-
sity profiles. For two neutrinos mixing, we have used the fit values of neutrino oscillation parameters from solar, atmospheric, and accelerator experiments and analyzing the resonance condition we found that the resonance lengths are the largest and resonance densities are the smallest for solar parameters and using accelerator parameters we have obtained the opposite situation, the resonance lengths are the smallest and resonance densities are the largest. The most favorable condition for high-energy neutrinos to oscillate resonantly before going out of the source is given through atmospheric parameters and these conversions would be pure adiabatic. For three neutrino mixing, we have calculated the ratio flavor on the surface of the source as well as that expected on Earth. Our analysis shows that deviations from 1:1:1 are obtained at different energies and places along the jet, which is given in table 2. From analysis of half probability we also show that neutrinos may oscillate depending on their energy and the parameters of neutrino experiments. As a particular case, when the three-flavor parameters are considered (fig. 2), we obtain that neutrino energies above $\geq 10 \text{ TeV}$ can hardly oscillate, obtaining the same result given by Osorio Oliveros, Sahu & Sanabria (2013).

As shown, depending on the flavor ratio obtained on Earth we could differentiate the progenitor, its density profile at different depths in the source, as well as understand similar features between IGRBs and core collapse supernovae. Distinct times of arrival of neutrinos (Abbasi et al. 2007; IceCube Collaboration et al. 2013b) would be a compelling evidence that choked jets are bright in different places in the star (Bartos, Dasgupta & Márka 2012). These observations in detectors such as IceCube, Antares and KM3Net would be a compelling evidence that choked jets are bright in different places in the star (Bartos, Dasgupta & Márka 2012). These observations in detectors such as IceCube, Antares and KM3Net would be a compelling evidence that choked jets are bright in different places in the star (Bartos, Dasgupta & Márka 2012).

### Table 2

| $E$ (GeV) | $\phi^0_{\nu_e} : \phi^0_{\nu_{\mu}} : \phi^0_{\nu_\tau}$ (L=10$^{11}$ cm) | $\phi^0_{\nu_e} : \phi^0_{\nu_{\mu}} : \phi^0_{\nu_\tau}$ (L=10$^{12}$ cm) | $\phi^0_{\nu_e} : \phi^0_{\nu_{\mu}} : \phi^0_{\nu_\tau}$ (L=10$^{13}$ cm) |
|----------|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| 0.024    | 1.046:1.008:0.956                               | 0.925:1.031:1.045                                 | 0.998:1.011:0.991                                 |
| 0.178    | 0.889:1.049:1.062                               | 1.021:1.000:0.978                                 | 0.888:1.049:1.063                                 |
| 0.428    | 1.033:1.000:0.966                               | 0.954:1.053:1.047                                 | 0.893:1.046:1.061                                 |
| 3        | 0.979:1.010:1.011                               | 0.883:1.049:1.067                                 | 0.883:1.050:1.067                                 |
| 68.5     | 1.065:0.998:0.936                               | 1.063:0.999:0.939                                 | 1.042:1.001:0.957                                 |

**REFERENCES**

Abbari R. et al., 2012, Astroparticle Physics, 35, 615

Abe K., et al., 2011, Physical Review Letters, 107, 241801

Aguilar-Arevalo A. A., et al., 2007, Physical Review Letters, 98, 231801

Aguilar-Arevalo A. A., et al., 2009, Physical Review Letters, 102, 101802

Aguilar-Arevalo A. A., et al., 2010, Physical Review Letters, 105, 181801

Aharmim B., et al., 2011, ArXiv e-prints

Ahn M. H., et al., 2006, Phys. Rev. D, 74, 072003

Akademov E. K., Johansson R., Lindner M., Ohlsson T., Schwetz T., 2004, Journal of High Energy Physics, 4, 78

Alvarez-Muñiz J., Halzen F., 2002, ApJ, 576, L33

Alvarez-Muñiz J., Mészáros P., 2004, Phys. Rev. D, 70, 123001

Ando S., Beacom J. F., 2005, Physical Review Letters, 95, 061103

Araki T., et al., 2005, Physical Review Letters, 94, 081801

Arbruster B., et al., 2002, Phys. Rev. D, 65, 112001

Arnett D., 1991, ApJ, 383, 295

Athanasopoulos C., et al., 1996, Physical Review Letters, 77, 3082

Athanasopoulos C., et al., 1998, Physical Review Letters, 81, 1774

Athanassopoulos C., et al., 2005, Phys. Rev. D, 71, 083007

Atoyan A., Dermer C. D., 2001, Physical Review Letters, 87, 221102

Barniol Duran R., Bošnjak Ž., Kumar P., 2012, MNRAS, 424, 3192

Bartos I., Dasgupta B., Mármara S., 2012, Phys. Rev. D, 86, 083007

Becker J. K., Biermann P. L., 2009, Astroparticle Physics, 31, 138

Bethe H. A., Pizzochero P., 1990, ApJ, 350, 1338

Becker J. K., Biermann P. L., 2009, Astroparticle Physics, 31, 138

Becker J. K., Biermann P. L., 2009, Astroparticle Physics, 31, 138

Becker J. K., Biermann P. L., 2009, Astroparticle Physics, 31, 138

Bethe H. A., Pizzochero P., 1990, ApJ, 350, L33

Chen H. H., 1985, Physical Review Letters, 55, 1534

Chevalier R. A., Soker N., 1989, ApJ, 341, 867

Cholis I., Hooper D., 2012, ArXiv e-prints

Church E. D., Eitel K., Mills G. B., Steidl M., 2002, Phys. Rev. D, 66, 013001

Costantini M. L., Vissani F., 2005, Astroparticle Physics, 23, 477

Dermier C. D., Atoyan A., 2003, Physical Review Letters, 91, 071102

Dermier C. D., Menou G., 2009, High Energy Radiation from Black Holes: Gamma Rays, Cosmic Rays, and Neutrinos

Dighe A. S., Smirnov A. Y., 2000, Phys. Rev. D, 62, 033007

Fraija N., González M. M., Lee W. H., 2012, ApJ, 751, 33

González-Garcia M. C., 2011, Physics of Particles and Nuclei, 42, 345

Gonzalez-Garcia M. C., Maltoni M., 2008, Phys. Rep., 460, 1

Gonzalez-Garcia M. C., Nir Y., 2003, Reviews of Modern Physics, 75, 345

ACKNOWLEDGEMENTS

We thank the referee for a critical reading of the paper and valuable suggestions. We also thank B. Zhang, K. Murase, William H. Lee, Fabio de Colle, Enrique Moreno and Antonio Marinelli for useful discussions. NF gratefully acknowledges a Luc Binette-Fundación UNAM Postdoctoral Fellowship.
GeV - PeV Neutrino Production and Oscillation in hidden jets from GRBs

Gupta N., Zhang B., 2007, Astroparticle Physics, 27, 386
Hjorth J., et al., 2003, Nature, 423, 847
IceCube Collaboration et al., 2013a, ArXiv e-prints
IceCube Collaboration et al., 2013b, ApJ, 763, 33
Kashlinsky A., Waxman E., 2005, Physical Review Letters, 95, 181101
Kumar P., Barniol Duran R., 2010, MNRAS, 409, 226
Kuo T. K., Pantalone J., 1989, Reviews of Modern Physics, 61, 937
Learned J. G., Pakvasa S., 1995, Astroparticle Physics, 3, 267
Pantselous A. G., Tzamarias S. E., KM3NeT consortium f. t., 2012, ArXiv e-prints
Liu R.-Y., Wang X.-Y., 2013, ApJ, 766, 73
MacLachlan G. A. et al., 2013, MNRAS, 432, 857
Matzner C. D., McKee C. F., 1999, ApJ, 510, 379
Mena O., Moccioli I., Razzouk S., 2007, Phys. Rev. D, 75, 063003
Meszaros P., Rees M. J., Wijers R. A. M. J., 1998, ApJ, 499, 301
Murase K., Ioka K., Nagataki S., Nakamura T., 2006, ApJ, 651, L5
Nellen L., Mannheim K., Biermann P., 1993, Phys. Rev. D, 47, 5270
Osorio Oliveros A. F., Sahu S., Sanabria J. C., 2013, ArXiv e-prints
Pradier T., Antares Collaboration, 2010, Classical and Quantum Gravity, 27, 194004
Razzouk S., Meszaros P., Waxman E., 2004, Physical Review Letters, 93, 181101
Razzouk S., Meszaros P., Waxman E., 2005, Modern Physics Letters A, 20, 2351
Razzouk S., Smirnov A. Y., 2010, Journal of High Energy Physics, 3, 31
Sacahui J. R., Fraija N., González M. M., Lee W. H., 2012, ApJ, 755, 127
Sahu S., Zhang B., 2010, Research in Astronomy and Astrophysics, 10, 943
Shen R., Kumar P., Piran T., 2010, MNRAS, 403, 229
Shigeyama T., Nomoto K., 1990, ApJ, 360, 242
Shirai J., KamLAND Collaboration, 2007, Nuclear Physics B Proceedings Supplements, 168, 77
Stanek K. Z., et al., 2003, ApJ, 591, L17
Stecker F. W., 1968, Physical Review Letters, 21, 1016
Stecker F. W., Done C., Salamon M. H., Sommers P., 1991, Physical Review Letters, 66, 2697
Szabo A. P., Protheroe R. J., 1994, Astroparticle Physics, 2, 375
Taboada I., 2010, Phys. Rev. D, 81, 083011
the KamLAND Collaboration, Mitsui T., 2011, Nuclear Physics B Proceedings Supplements, 221, 193
Wang X.-Y., Razzouk S., Meszaros P., Dai Z.-G., 2007, Phys. Rev. D, 76, 083009
Waxman E., Bahcall J., 1997, Physical Review Letters, 78, 2292
Waxman E., Loeb A., 2001, Physical Review Letters, 87, 071101
Wendell R., et al., 2010, Phys. Rev. D, 81, 092004
Wolfenstein L., 1978, Phys. Rev. D, 17, 2369
Woosley S. E., Langer N., Weaver T. A., 1993, ApJ, 411, 823
Figure 1. Proton cooling time scales in the comoving frame for different processes as a function of proton energy ($E_p$) when the shell collisions take place at $r = 6 \times 10^{10}$ cm and different magnetic fields. Synchrotron radiation ($t'_{\text{sync}}$), IC+KN scattering ($t'_{\text{ic+KN}}$), Bethe-Heitler ($t'_{\text{BH}}$), shock acceleration time ($t'_{\text{acc}}$).

Figure 2. Proton cooling time scales in the comoving frame for different processes as a function of proton energy ($E_p$) when the shell collisions take place at $r = 6 \times 10^{10}$ cm and different magnetic fields. Synchrotron radiation ($t'_{\text{sync}}$), IC+KN scattering ($t'_{\text{ic+KN}}$), Bethe-Heitler ($t'_{\text{BH}}$), shock acceleration time ($t'_{\text{acc}}$).
π/ K - synchrotron radiation ($\tau'_{(\pi/K)_{\text{syn}}} \), π/ K - decay ($\tau'_{(\pi/K)_{\text{decay}}} \),
π/ K - synchrotron and hadronic radiation ($\tau'_{\text{cool}} \).
Figure 5. Neutrino energy created at \(6 \times 10^9\) cm (above) and \(6 \times 10^{10}\) cm (below) for different interaction processes as a function of magnetic equipartition parameter.

Figure 6. In the top figure, Density profiles ([A], [B] and [C]) given by eqs. (25), (26) and (27), respectively are plotted. Also from the resonance condition, we plot the resonance density as a function of resonance length for High-energy neutrinos. In the bottom figure, the flip probability is plotted as a function of neutrino energy for density profiles [A] (eq. 25), [B] (eq. 26) and [C] (eq. 27). We have used the best parameters of the three-flavor neutrino oscillation.

Figure 7. Density profiles ([A], [B] and [C]) given by eqs. (25), (26) and (27), respectively are plotted. Also from the resonance condition, we plot the resonance density as a function of resonance length for High-energy neutrinos. We have used the best parameters of the two-flavor solar (above), atmospheric (medium) and accelerator (below) neutrino oscillation.
Figure 8. The flip probability is plotted as a function of neutrino energy for density profiles [A] (eq. 25), [B] (eq. 26), and [C] (eq. 27). On the top figure we use solar parameters, on the middle figure we use atmospheric parameters and on the bottom figure we use accelerator neutrinos.

Figure 9. The flip probability is plotted as a function of neutrino energy for density profiles [A] (eq. 25), [B] (eq. 26), and [C] (eq. 27). We have used the best parameters of the three-flavor neutrino oscillation.

Figure 10. We have plotted the oscillation probability as a function of neutrino energy for neutrinos produced at radii $r = 6 \times 10^9$ cm and $r = 6 \times 10^{10}$ cm. In the top, middle and bottom figures we plot the oscillation probabilities when neutrinos are moving at $r = 10^{10}$ cm, $r = 10^{11}$ cm and $r = 10^{12}$ cm, respectively.
Figure 11. To have a better visibility of bottom figure 10, we separate the oscillation probabilities like, figures from up to down, $P_{e,i}$ for $e, \mu, \tau$ (first one), $P_{\mu\mu}$ (second one), $P_{\mu\tau}$ (third one) and $P_{\tau\tau}$ (four one).

Figure 12. We plot the oscillation probability when neutrinos are produced at a radius $r = 6 \times 10^9$ cm and are propagating through the jet direction for four energies: $E_{\nu} = 178$ GeV (first figure), $E_{\nu} = 428$ GeV (second figure), $E_{\nu} = 3$ TeV (third figure) and $E_{\nu} = 69$ TeV (four figure).
Figure 13. We plot the oscillation probability when neutrinos are produced at a radius \( r = 6 \times 10^{10} \text{ cm} \) and are propagating through the jet direction for four energies: \( E_\nu = 178 \text{ GeV} \) (first figure), \( E_\nu = 428 \text{ GeV} \) (second figure), \( E_\nu = 3 \text{ TeV} \) (third figure) and \( E_\nu = 69 \text{ TeV} \) (four figure).