TeV Neutrino Flavor Ratio from Choked GRBs

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**LGRBs:** Long-duration bursts are now generally reckoned to involve energy released along narrow jets during a specific kind of hypernova (a violent supernova) involving the final demise of stars that started their lives with masses of 40 to 100 times that of the Sun. In such cases, the remnant stellar core collapses immediately to form a black hole. The close connection between long gamma-ray bursts and Type Ib/c supernovae points to the progenitor stars being almost exclusively fast-spinning Wolf-Rayet stars.
**Long Gamma-Ray Bursts (LGRBs)**

Observationally only a small fraction of core collapse SNe are associated with GRBs \((10^{-3})\).

They correspond to those Jets that break through the stellar envelope and reach highly relativistic speed (Lorentz Factor \(\Gamma \sim 100\)).
What happens when the jet is mildly relativistic?

The jet never makes its way out from the envelope. Either due to Small Energy Budget, Extended Massive Envelope, Forming a Choked Jet.

Protons are accelerated up to $\sim 10^5$ GeV in the internal shock and collide with $\sim 1$ keV X-Ray photons to produce $\sim$ few TeV neutrinos.
The possibility of detection of Neutrinos from High Luminosity (HL) GRB (GRB030329) by ICECUBE is studied earlier.

In general the diffuse neutrino background from whole GRB population is of great observational interest.

Observation of low luminosity (LL), Long GRBs:

- GRB060218/SN 2006aj (SWIFT), z=0.0331
- GRB980425/SN 1998bw (BeppoSAX), z=0.0085

May be many of these Core Collapse are unsuccessful in producing successful jets!!
There number can be high?
In the Choked GRBs

$10^5$ GeV

$\sim 1$ keV

$\sim$ TeV

Neutrino Flux Ratio 1:2:0
Main source of neutrino production due to pion decay

At the production site the flux ratio is (~TeV neutrinos)

$$\Phi^0_{\nu_e} : \Phi^0_{\nu_\mu} : \Phi^0_{\nu_\tau} = 1 : 2 : 0$$

Vacuum oscillation on their way to Earth

$$\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} = 1 : 1 : 1$$
For High Energy Neutrinos $\sim$ PeV, muon energy is degraded before decaying to low energy neutrinos implies

\[
\Phi^0_{\nu_e} : \Phi^0_{\nu_\mu} : \Phi^0_{\nu_\tau} = 0 : 1 : 0
\]

Vacuum oscillation on their way to Earth

\[
\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} = 1 : 1.8 : 1.8
\]

Kasti & Waxman, PRL 95 (05)
What happens if matter effect on neutrino is taken into account in the Choked Jets?

\[
i \frac{d}{dt} \begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{bmatrix} V - \Delta \cos 2\theta & \frac{\Delta}{2} \sin 2\theta \\ \frac{\Delta}{2} \sin 2\theta & 0 \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix}
\]

\[
\Delta = \Delta \frac{m^2}{2 E_\nu}
\]

\[
V = \sqrt{2} G_F N_e
\]

The transition probability as a function of distance:

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

\[
\omega = \left[ \left( V - \Delta \cos 2\theta \right)^2 + \Delta^2 \sin^2 2\theta \right]^{1/2}
\]
Once the neutrinos are produced due to decay at a point, they will propagate away. If the density of the medium is such that the condition

\[ \sqrt{2} G_F N_e = \Delta \cos 2 \theta \]

**Resonance Condition**

Is satisfied (not for anti-nu), the resonant conversion from one flavor to another with maximum amplitude can occur. The resonance density at this point is

\[ \rho_R = 1.32 \, g \, cm^{-3} \, \frac{\Delta m^2}{E_{\nu,12.7}} \cos 2 \theta \]

Resonance length is

\[ l_R = \frac{2 \pi}{\Delta \sin 2 \theta} = 1.24 \times 10^9 \, cm \left( \frac{E_{\nu,12.7}}{\Delta m^2} \right) \frac{1}{\sin 2 \theta} \]
If the resonance region is wide enough the transition can be total. We can define a resonance width for which the amplitude can be $\frac{1}{2}$.

**Width** is $\Gamma = 2 \Delta m^2 \sin 2 \theta$

This corresponds to a length scale

$$\delta r_R = \frac{2 \tan 2 \theta}{\left| \frac{1}{N_e} \frac{dN_e}{dr} \right|_R}$$

For $\delta r_R > l_R$ there can be enough time for $\nu_e$ to stay in the resonance region to convert into $\nu_\mu (\nu_\tau)$.

But to know the above condition we need to know the density profile $dN_e/dr$. 
Density Profile of a Pre-Supernova Star

The density profile is difficult to probe observationally.

Numerical Simulations assumes

\[ \rho(r) = \rho_0 \left( \frac{R_*}{r} - 1 \right)^n \]

Depends on the type of star.

For Blue Super Giant (BSG)

\[ n = 3, \frac{3}{2} \]

Radiative / Convective

\[ R_* = 3 \times 10^{12} \text{ cm}, \quad \rho_0 = 3 \times 10^{-5} \text{ g/cm}^3 \]

In some models, He core extends \( r_{\text{(He)}} \sim 10^{11} \text{ cm} \), with density \( 10^{-3} \text{ g/cm}^3 \).
The condition \( \delta r_R > l_R \)

Translates into

\[
n < 2 \tan 2 \theta \left( 1 - \frac{l_R}{R^*} \right)
\]

For \( l_R \geq R^* \), \( n < 0 \) (unphysical)

No neutrino oscillation is expected inside the stars.

On the other hand, if

\[
l_R \ll R^*
\]
The constraint \( n < 2 \tan 2 \theta \)

May satisfy in some stars for some oscillation parameters.

1. ) Solar Neutrino Parameters from SNO+KamLand

\[
6 \times 10^{-5} \, eV^2 < \Delta m^2 < 10^{-4} \, eV^2 \\
0.64 < \sin^2 2 \theta < 0.96
\]

Best Fit point

\[
\Delta m^2 \sim 7.1 \times 10^{-5} \, eV^2, \quad \sin^2 2 \theta \sim 0.69
\]
Here

\[
\rho_{R,SNO} \approx 5.2 \times 10^{-5} \text{ g cm}^{-3} E_{\nu,12.7}^{-1}
\]

\[
l_{R,SNO} \approx 2.1 \times 10^{13} \text{ cm } E_{\nu,12.7}
\]

\[l_R \gg R_\ast \quad \text{For a Typical BSG}\]

No resonant Oscillation in this Case
2. ) Super Kamiokande
(Atmospheric Neutrino Parameters)

\[ 1.9 \times 10^{-3} \, \text{eV}^2 < \Delta m^2 < 3 \times 10^{-3} \, \text{eV}^2 \]

\[ 0.9 < \sin^2 2\theta < 1.0 \]

Best Fit point

\[ \Delta m^2 \sim 2.5 \times 10^{-3} \, \text{eV}^2 , \quad \sin^2 2\theta \sim 0.9 \]

Gives

\[ \rho_{R,SK} \approx 1.0 \times 10^{-3} \, \text{g cm}^{-3} \, E^{-1}_{\nu,12.7} \]

\[ l_{R,SK} \approx 5.2 \times 10^{11} \, \text{cm} \, E_{\nu,12.7} \]

\[ n < 4.96, \text{We take } n = 3 \text{ here} \]
Blue Super Giant, density profile for Simulation
It suggests that within a nominal BSG progenitor multi-TeV neutrino oscillation occur for oscillation parameters inferred by atmospheric neutrino data.

A similar analysis suggests that the same conclusion applies to other BSG progenitors or He stars with extended envelope ($R^* \sim 10^{12}$ cm).

Does not apply to He stars with $R^* \sim 10^{11}$ cm or other more compact stars.

GRBs are associated with Type Ic SNe (without He) are not preferred sources of TeV neutrino oscillation.

Instead we identify Choked GRBs with heavy envelope as interesting source of Resonant TeV neutrino oscillation.
For a full oscillation

\[ \nu_e \leftrightarrow \nu_\mu, \nu_\tau \]
\[ \nu_\mu \leftrightarrow \nu_e \]
\[ \bar{\nu} - \text{no resonant oscillation} \]

Survival Probability of each flavor

\[ \left( \frac{1}{3} + \frac{1}{2} \right) : \left( \frac{1}{3} + \frac{1}{2} + 1 \right) : \frac{1}{3} \]

Ratio on the surface of the star

5 : 11 : 2

Different from 1 : 2 : 0
Vacuum Oscillation of these TeV neutrinos on their way to Earth

\[ \Phi_{\nu_\alpha}^{\text{Earth}} = \sum_\beta P_{\alpha \beta} \Phi_{\nu_\beta}^{\text{Surface}} \]

\[ P_{\alpha \beta} \rightarrow \text{Vacuum oscillation prob.} \]

Large Mixing Angle Solution

\[ \theta_{12} = 34^\circ \pm 2.5^\circ, \quad \theta_{23} = 45^\circ \pm 6^\circ, \quad \theta_{13} = 0 \pm 8^\circ, \quad \delta = 0 \]

\[ P_{ee} \approx 0.57, \quad P_{e\mu} = P_{e\tau} = 0.215, \quad P_{\mu\mu} = P_{\mu\tau} = P_{\tau\tau} \approx 0.393 \]

\[ 1 : (1.095 \pm 0.012) : (1.095 \pm 0.012) \]
Maximal Mixing among muon and tau neutrinos

\[ P_{ee} \approx 1, P_{\mu\mu} = P_{\mu\tau} = P_{\tau\tau} \approx 1/2 \]

\[ 1 : 1.3 : 1.3 \]
The deviation from 1:1:1 on Earth may be tested by upcoming ICECUBE.

The flavor ratios can in principle be deduced from the relative rates of showers, muon tracks and the tau lepton signal. But tau signal is low for TeV neutrinos.

ICECUBE can distinguish between shower like events and muon track events.

By assuming the $\text{symmetry}$, fraction can be extracted from the measured Muon to shower ratio.
\[ E_\nu^2 \frac{dN_\nu}{dE_\nu} = 10^{-7} \text{GeV cm}^{-2} \text{s}^{-1} \]

1 year

0.28 → 3.5

0.33 → 3
Conclusions:

We have calculated the neutrino flux ratio on Earth for ~ TeV neutrinos by considering the medium effect of the choked GRBs. Which is different from 1:1:1.

This flux Ratio is energy dependent. In principle this can be detected by ICECUBE from the ratio of track to shower ration of upward going muons.

Nearby bright neutrino bursts would significantly increase the flux and reduce the uncertainty and makes a better case for the change of flavor ratio.