A STANDARD SOURCE FOR HIGH ENERGY NEUTRINO ASTRONOMY

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ABSTRACT

We discuss here a standard source of high energy neutrinos composed of a source of accelerated particles imbedded in a cloud of low density gas. The main mechanism of neutrino production in the source is pp-collision, and the main process of detection is through muons produced underground by the neutrinos. The flux of neutrino-produced muons is computed for sources with different spectral index.

1. Introduction. High energy neutrinos ($E_\nu \gtrsim 10$ GeV) can be generated in cosmic sources as a result of the interactions of accelerated protons with the ambient gas, through the chain of pions (kaons) decays, as well as charged mesons decay (prompt neutrinos). In the past, the possibility to detect high energy neutrinos was discussed mainly in connection with huge detectors, with an area of order 1 km^2, as the DUMAND project. The aim of this paper is to discuss high energy neutrino astronomy for relatively small (area $S \sim 100\ m^2$) underground detectors, and to consider a "standard source" of high energy cosmic neutrinos to which refer when considering (see Berezinsky et al., these proceedings) the real astrophysical sources.

The main process of neutrino production in the source is pp-collisions (which implies also p-nuclei collisions). In some cases prompt neutrinos can dominate, while usually $p\gamma$ neutrinos have too large energies and consequently too small fluxes to be detected in small detectors. The main reaction for neutrino detection is $\nu_\mu + N \rightarrow \mu + X$, for which at high energy muons retain the same direction of the parent neutrinos, so that the source is seen within the resolution angle of the detector. For a detector located deep underground, and for a source in antivertical direction, the atmospheric muon flux is negligible along the direction of the source, and the background is mainly due to the atmospheric neutrinos.

2. The standard source. Our standard neutrino source is a source of accelerated particles imbedded in a cloud of low density gas (1), in which neutrinos are produced through the chain of pions and kaons decays, which follows the pp-collisions. We assume that the column density of the cloud is $x \gg x_n \sim 70\ g/cm^2$, and at the same time transparent to neutrinos. In our calculations we used the follo-

wing spectrum of the accelerated particles:

$$\dot{N}_p(E)\, dE = (\gamma - 1)\gamma \left(\frac{E}{E_o} + 1\right)^{-(\gamma+1)} \frac{L_p}{E_o} \frac{dE}{E_o} \qquad (1)$$

where $\dot{N}_p(E)$ is the number of protons with kinetic energy E produced per second by the source, γ is the exponent of the integral spectrum, and L_p is the cosmic ray luminosity of the source: $L_p = \int_0^\infty E\, \dot{N}_p(E)\, dE$. In all our formulae the energy is given in GeV, $E_o = 1$ GeV, and L_p is given in GeV/s. For $E \gg E_o$ the neutrino flux at the Earth is given by(2):

$$j_\nu(E)\, dE = \frac{L_p}{4\pi r^2} \frac{(\gamma - 1)}{(1-\alpha)} (\varphi_\nu + \varphi_{\tilde{\nu}})\, E^{-(\gamma+1)}\, dE \qquad (2)$$

where φ_ν and $\varphi_{\tilde{\nu}}$ are the neutrino yields, $\alpha \sim 0.5$ is the fraction of energy retained by a nucleon in a nuclear collision, and r is the distance to the source. This flux is accompanied by an equilibrium muon flux that can be calculated from the kinetic equilibrium $\frac{d}{dE}\left[\beta(E_\mu)\, j_\mu(E_\mu)\right] = G(E)$, as:

$$j_\mu(E_\mu) = \frac{N_A}{\beta(E_\mu)} \int_{E_\mu}^{\infty} dE \int_{E}^{\infty} \frac{dE_\nu}{E_\nu} j_\nu(E_\nu) \int_0^1 dx \left[\eta \frac{d^2\sigma_\nu(E_\nu)}{dx\, dy} + \bar{\eta} \frac{d^2\sigma_{\tilde{\nu}}(E_{\tilde{\nu}})}{dx\, dy}\right] \qquad (3)$$

where $N_A = 6.02\; 10^{23}$ is the Avogadro number, $\beta(E_\mu) = a + bE_\mu$ is the muon energy loss expressed in GeV cm^2/g with the values of a and b given by (3), $j_\nu(E_\nu)$ is the $\nu_\mu + \tilde{\nu}_\mu$ flux, $\eta = \varphi_\nu/(\varphi_\nu + \varphi_{\tilde{\nu}})$ and $\bar{\eta} = \varphi_{\tilde{\nu}}/(\varphi_\nu + \varphi_{\tilde{\nu}})$ are the fractions of ν_μ and $\tilde{\nu}_\mu$ neutrinos in the flux, $y = E_\mu/E_\nu$, and x is the scaling variable. The differential cross-sections can be written as:

$$\frac{d^2\sigma_\nu}{dx\, dy} = \frac{G_F^2 (2\, E_\nu m_n + m_n^2)}{2\pi} \frac{A(x,Q^2) + \bar{B}(x,Q^2)\, y^2}{(1 + Q^2/m_W^2)^2}$$

$$\frac{d^2\sigma_{\tilde{\nu}}}{dx\, dy} = \frac{G_F^2 (2\, E_\nu m_n + m_n^2)}{2\pi} \frac{\bar{A}(x,Q^2) + B(x,Q^2)\, y^2}{(1 + Q^2/m_W^2)^2} \qquad (4)$$

where $m_n = 0.94$ GeV is the nucleon mass, $m_W = 81$ GeV is the W boson mass, $G_F = 1.17\; 10^{-5}\; GeV^{-2}$, and the form factors can be expressed through the quark structure functions $x(u_v + d_V)$ and xS, with $S = 6\bar{u}$, as:

$$\begin{aligned} \bar{A}(x,Q^2) &= 2\bar{B}(x,Q^2) = \frac{2}{3} x\, S(x,Q^2) \\ A(x,Q^2) &= x\left[u_V(x,Q^2) + d_V(x,Q^2)\right] + \frac{2}{3} x\, S(x,Q^2) \\ B(x,Q^2) &= x\left[u_V(x,Q^2) + d_V(x,Q^2)\right] + \frac{1}{3} x\, S(x,Q^2) \end{aligned} \qquad (5)$$

In our calculations we used the structure functions given by[4]. Q^2 is defined as $2m_n E_\mu x(1-y)/y$ when larger than 4 GeV^2, and it is assumed $Q_o^2 = 4\ GeV^2$ when smaller than Q_o^2. Inserting (4) and (5) into (3), one obtains, for a power law neutrino spectrum:

$$j_\mu(E_\mu) = j_\nu(E_\mu) \frac{\sigma_F N_A}{\beta(E_\mu)} \frac{G_F E_\mu^2 m_n}{\pi} i_\gamma(E_\mu) \qquad (6)$$

where $\sigma_F = 4.54\ 10^{-33}\ cm^2$ is the Fermi constant and

$$i_\gamma(E_\mu) = \int_0^1 dz\, z^{\gamma-2} \int_0^1 dy\, y^{\gamma-1} \int_0^1 \frac{dx}{(1+Q^2/m_W^2)^2} \cdot \qquad (7)$$

$$\cdot \left[\eta\, A(x,Q^2) + \bar{\eta}\, \bar{A}(x,Q^2) + y^2\left\{\eta\, \bar{B}(x,Q^2) + \bar{\eta}\, B(x,Q^2)\right\}\right]$$

where $Q^2 = 2m_n E_\mu x(1-y)/yz$ if larger than 4 GeV^2, and $Q^2 = 4\ GeV^2$ otherwise. The integral muon flux can thus be expressed by:

$$j_\mu(>E_\mu) = j_\nu(>E_\mu) \frac{\gamma\, \sigma_F N_A G_F E_\mu^2 m_n}{\pi} \int_0^1 du\, u^{\gamma-3} \frac{i_\gamma(E_\mu/u)}{\beta(E_\mu/u)} \qquad (8)$$

and the number of muons crossing an underground detector with area S during the time t is given by:

$$n_\mu(>E_\mu) = j_\mu(>E_\mu)\, S\, t \qquad (9)$$

We computed the values of $n_\mu(>E_\mu)$ for $S = 100\ m^2$, $t = 1$ year, and our standard neutrino sourcewith a cosmic ray luminosity $L_p = 10^{43}$ erg/s at the distance r = 10 kpc, for different values of the exponent of the integral spectrum. Table 1 gives the results of our calculations.

3. Conclusions. From the values of $n_\mu(>E_\mu)$ reported in table 1, the following conclusions can be inferred:

i) to detect with a $S = 100\ m^2$ area detector a galactic source at the distance of 10 kpc, a cosmic ray luminosity of order $L_p = 10^{43}$ erg/s is needed. Such a large luminosity can be provided only by supernovae explosions or young pulsars.

ii) to detect extragalactic neutrino sources, the scale of luminosity is $L_p \approx 10^{47}$ erg/s at the distance r = 1 Mpc, and $L_p \approx 10^{49}$ erg/s at r = 10 Mpc.

Integral spectral index γ	E_μ (GeV) 10	30	100	300	1000
1.1	$1.2\ 10^3$	$1.2\ 10^3$	$1.1\ 10^3$	$9.3\ 10^2$	$6.7\ 10^2$
1.2	$6.9\ 10^2$	$6.6\ 10^2$	$6.0\ 10^2$	$4.9\ 10^2$	$3.3\ 10^2$
1.3	$3.1\ 10^2$	$2.9\ 10^2$	$2.6\ 10^2$	$1.9\ 10^2$	$1.3\ 10^2$
1.4	$1.3\ 10^2$	$1.2\ 10^2$	$1.0\ 10^2$	$7.4\ 10^1$	$4.5\ 10^1$
1.5	$5.5\ 10^1$	$4.9\ 10^1$	$4.0\ 10^1$	$2.8\ 10^1$	$1.6\ 10^1$
1.6	$2.3\ 10^1$	$2.0\ 10^1$	$1.6\ 10^1$	$1.0\ 10^1$	5.3
1.7	$1.0\ 10^1$	8.6	6.2	3.9	1.8
1.8	4.7	3.7	2.5	1.5	$6.4\ 10^{-1}$
1.9	2.2	1.6	1.0	$5.7\ 10^{-1}$	$2.2\ 10^{-1}$
2.0	1.1	$7.4\ 10^{-1}$	$4.4\ 10^{-1}$	$2.2\ 10^{-1}$	$8.0\ 10^{-2}$
2.1	$5.3\ 10^{-1}$	$3.4\ 10^{-1}$	$1.9\ 10^{-1}$	$8.8\ 10^{-2}$	$2.9\ 10^{-2}$
2.2	$2.7\ 10^{-1}$	$1.6\ 10^{-1}$	$8.0\ 10^{-2}$	$3.5\ 10^{-2}$	$1.0\ 10^{-2}$

Table 1: number of muons with energy higher than E_μ crossing in 1 year an underground detector with area $S = 100\ m^2$, for our standard source with cosmic ray luminosity $L_p = 10^{43}$ erg/s at the distance $r = 10$ kpc.

References

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