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Extraterrestrial High Energy Neutrino Fluxes

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EXTRATERRESTRIAL HIGH ENERGY NEUTRINO FLUXES

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Abstract

Using the most recent cosmic ray spectra up to $2 \times 10^{20} \text{ eV}$, production spectra of high energy $\nu$'s from cosmic ray interactions with interstellar gas and extragalactic interactions of ultrahigh energy cosmic rays with $3K$ universal background photons are presented and discussed. Estimates of the fluxes from cosmic diffuse sources and the "nearby" quasar 3C273 are made using the generic relationship between secondary $\nu$'s and $\gamma$'s and using recent $\gamma$-ray satellite data. These $\gamma$-ray data provide important upper limits on cosmological $\nu$'s. Quantitative estimates of the observability of high energy $\nu$'s from the inner galaxy and 3C273 above atmospheric background for a DUMAND type detector are discussed in the context of the Weinberg-Salam model with $\sin^2 \theta_W = 0.2$ and including the atmospheric background from the decay of charmed mesons. Constraints on cosmological high energy neutrino production models are also discussed. It appears that important high energy neutrino astronomy may be possible with DUMAND, but very long observing times are required.

1. Introduction

There have been a number of recent papers estimating high-energy neutrino fluxes and spectra from various astrophysical processes$^{3-6)}$. In this work, I reexamine the problem by 1) presenting the results of a detailed calculation of galactic $\nu$-production in cosmic-ray interactions with interstellar gas and extragalactic $\nu$-production by interactions of ultrahigh energy cosmic rays with the $3K$ universal background radiation, 2) using these results together with present $\gamma$-ray observations to predict neutrino fluxes and event rates, and 3) discussing the problem of observing extraterrestrial $\nu$ fluxes above the atmospheric background.

2. Production Rates

The first basic production process for high energy cosmic neutrinos is the decay of charged pions produced in cosmic ray interactions with interstellar gas, primarily $pp$ interactions. This process will henceforth be referred to as "$pp$", although the effects of $\alpha p$, $pHe$, and $\alpha He$ interactions are included in the calculation. The second process involves the photoproduction of $\pi$-mesons by interaction of ultrahigh energy cosmic rays with the $3K$ universal microwave background radiation (henceforth referred to as $\nu p$) and subsequent meson decay. Both of these types of interactions involve the accompanying production of $\pi^+$ mesons and their decay into cosmic $\gamma$-rays. Thus, the production rates of cosmic $\gamma$-rays and neutrinos are generically linked.

2.1 $pp$ Neutrino Production

A detailed discussion of the kinematics of the production and decay of secondary particles produced in "$pp$" interactions may be found in
Reference 7. Details of the γp process have also been previously given. In the present paper, the "pp" neutrino production spectrum was calculated for pp interactions up to 30 GeV by methods previously employed. At these energies, the parameters of Ganguli and Sreekantan were adopted for the rapidity distribution of charged pions. These authors have calculated γ-ray spectra which are in good agreement with those of the present author for γ-ray energies ≤ 10 GeV. At higher energies, the assumption of scaling gives larger fluxes and a flatter spectrum than those calculated using an "isobar + fireball" model in "pre-scaling days". It should be noted that the isobar + fireball (I-F) model is equivalent to a "leading-pion" model at high energies, since the isobar carries off ~ 50% of the energy and decays into a "leading pion". Both scaling and the I-F models produce a secondary spectrum which has the same spectral index as the primary spectrum in the high-energy limit.

The results of the "pp" production spectrum calculation are shown in Fig. 1. The two neutrino production spectra are given for an inter-
stellar hydrogen density of 1 cm$^{-3}$ so that it is really a production rate per hydrogen atom. The upper neutrino curve and the $\gamma$-ray production spectrum shown in the figure are calculated using a primary cosmic ray spectrum $I_p(E) = 2.35 E^{-2.67} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$ for $E_p > 10$ GeV and the lower curve is obtained for a primary spectrum $I_p(E_p) = 2.0 E^{-2.75} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$ (Ref. 14). (Most recently, Goodman, et al. have reported a primary proton spectrum of $1.5 E^{-2.72} \pm 0.06 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$ for $10^7 < E < 10^9$ GeV, consistent with the lower value given in Ref. 14.) The $\gamma$-ray spectrum is for all $\gamma$-rays from $\pi^0$-decay; the neutrino spectrum is for the $\nu\mu$ component. Since each pion decay results in one $\nu\mu$, one $\bar{\nu}\mu$ and one $\nu_e$ ($\bar{\nu}_e$), all of roughly the same energy, the total number of neutrinos produced (although of four different types) is a factor of 3 higher than that shown for $\nu\mu$'s. In this regard, it should be kept in mind that the cross section ratios given in Table 1 apply.

Table 1. $\nu N$ Cross Section Ratios

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Experimental Value (Refs. 54,55)</th>
<th>Theoretical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{eN}/\sigma_{\nu\mu N}$</td>
<td>$1.26 \pm 0.23$</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_{eN}/\sigma_{\nu N}$</td>
<td>$1.32 \pm 0.32$</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_{\nu\mu N}/\sigma_{eN}$</td>
<td>$0.40 \pm 0.12$</td>
<td>$\sim 1/3^*$</td>
</tr>
<tr>
<td>$\sigma_{\nu N}/\sigma_{eN}$</td>
<td>$0.38 \pm 0.02$</td>
<td>$\sim 1/3^*$</td>
</tr>
</tbody>
</table>

*valence quarks dominant

Figure 2 shows the integral galactic "pp" neutrino production spectrum.

2.2 $p \gamma$ Neutrino Production

The production rate for $p\gamma$ interactions has been calculated using the method of Ref. 9. As an example of the range of uncertainty, two different primary spectra were used, i.e. $I_p(E_p) = 6.4 \times 10^{-31} (E_p/10^{11})^{-2.6} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$ (Ref. 16) and
The integral fluxes in Figure 5 show galactic "pp" muon-neutrino and antineutrino fluxes for the central region $330^\circ \leq \ell \leq 40^\circ$ (CC) for $|b| \leq 20^\circ$ and $|b| = 10^\circ$, the anticenter region (AC) for $|b| = 20^\circ$ and the region of the galactic poles (GP). All of these spectra were normalized using the SAS-2 $\gamma$-ray data except for the CP curve which was obtained from Fig. 2 using a mean galactic path length of hydrogen gas $<n_L> = 3 \times 10^{20} \text{ cm}^{-2}$. The atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux shown in Fig. 5 is from Alkofer et al. who used the atmospheric muon data to derive their fluxes. The curve marked "other galaxies" is obtained by assuming a density of normal galaxies of $3 \times 10^{-76} \text{ cm}^{-3}$ (Ref. 27), assuming that they have the same $\gamma$-ray luminosity as our galaxy which is assumed to radiate $\frac{1}{3}$ of its $\gamma$-ray flux from $\eta^0$-decay. Note that since the predicted $\gamma$-ray spectrum...
from normal galaxies is considerably flatter than the observed extragalactic background, so that the limit on the γ-ray flux from other galaxies due to π⁰-decay is probably ~10⁻⁴ cm⁻² s⁻¹ sr⁻¹ above 100 MeV, the ν-background from π⁻-decay cannot be significantly higher than the curve marked "other galaxies".

Figure 6 shows the latitude distribution of νµ± calculated for energies above 1 TeV by extrapolation from the SAS-2 γ-ray data.

Fig. 3 - Calculated differential neutrino production spectra and background fluxes from photopion production by ultrahigh energy cosmic rays interacting with the 3K universal microwave background radiation.

4. Prompt Atmospheric Neutrinos

A new source of "prompt" neutrinos, possibly from the decay of charmed mesons, has been found in recent beam dump experiments at CERN. The ratio of the production rates of these neutrinos to π-production is ~10⁻⁴. A summary of the present data on charmed meson production is given in Reference 31. The importance of prompt neutrino production in the atmosphere at high energies has been discussed by several workers.

Figures 7 and 8 show the estimated fluxes of prompt (PR) muon and electron neutrinos for R = 10⁻⁴ and R = 10⁻³ (an R value between these two numbers appears most likely at this writing) together with the horizontal and vertical fluxes of atmospheric neutrinos and our estimates of the neutrino flux from the central part of the Galaxy. It can be seen that prompt neutrinos from the atmosphere have a spectrum and intensity which may mimic those of galactic neutrinos. Furthermore, even with directional information, a "large" background of prompt neutrinos may make it difficult to pick out a galactic "signal".

The neutrino flux from the inner Galaxy is expected to be confined
mainly to a narrow band in the sky (see Fig. 6) which, in principle, can be picked out above the atmospheric background with a detector such as the proposed DUMOND system with an angular resolution of better than $1/2^0$ above $10^3$ GeV energy (see section 6.1).

5. Event Rates

The $\nu N$ cross section rises linearly with $E_\nu$ and is $\sim 0.7 \times 10^{-36} E_\nu \text{cm}^2$ at accelerator energies. The $\nu N$ cross sections are $\sim 1/3 - 0.4$ of this value (see Table 1), although there is now evidence of an increase in this ratio to $\sim 0.6$ at $E_\nu \sim 100$ GeV, possibly due to a new flavor b-quark with $m_b \sim 5$ GeV. Owing to scaling violations and quantum chromodynamics, this ratio may approach unity at $E_\nu \gg 10^6$ GeV. Above a critical energy

$$E_\nu \sim \frac{M_W^2}{2M_p^2},$$

where $M_W$ is the mass of the intermediate vector boson and $M_p$ is the proton mass, the energy dependence of the cross section levels off to a logarithmic one. In the unified gauge theory of Weinberg and Salam, $M_W = 37.3 \csc \theta_W$, where $\theta_W$ is the mixing angle parameter expressing the relationship between the neutral current and electromagnetic coupling constants. The best experimentally determined value at present is $\sin^2 \theta_W \sim 0.2$ (Ref. 42) giving $M_W = 84$ GeV. The resulting $\nu N$ cross section as a function of $E_\nu$ is shown in Fig. 9.

Using the $\nu N$ cross section from Fig. 6 for $M_W = 84$ GeV (solid line) and a strictly linear cross section ($M_W = \infty$ dashed line) together with the calculated cosmic neutrino fluxes, expected event rates for $\nu$'s falling on a detector with an effective mass of $10^5$ tons of seawater as proposed for the DUMOND experiment were calculated and are given in Fig. 10. The dotted line marks the level corresponding to 100 events/yr. The upper "pp" curve is for the flux from the galactic central region using the production spectrum of Fig. 2, which is derived from the upper $\nu$-flux curve of Fig. 1. The curve marked $<pp>_{GAL}$ is for the galactic "pp" neutrinos averaged over $4\pi$ sr. Thus, on the average, one would expect an event rate of $\sim 40$ yr$^{-1}$ from galactic $\mu'$'s of energy $> 10$ TeV. If ultra-
6. Observability of Extraterrestrial Sources

The large fluxes of high energy neutrinos produced in the atmosphere as the result of the decay of secondary mesons arising in cosmic-ray interactions with atmospheric nuclei provide a significant background which, although useful from the point of view of neutrino physics, provides constraints on conducting neutrino astronomy observations. Below \( \sim 10 \) TeV, neutrinos from \( \pi \) and \( K \) decay create a noisy background problem which, because of the softness of their spectrum, gets worse at lower energies. At energies above \( \sim 10 \) TeV, the prompt neutrinos from D-decay take on more significance because of their harder spectrum which mimics the galactic spectrum (see section 4). One must therefore consider the
observability of various cosmic neutrino sources above fluctuations in this noisy atmospheric background.

6.1 Observability of the Inner Galaxy

The observability criterion adopted for quantitative estimates is the number of standard deviations a cosmic source signal would provide above atmospheric fluctuations. Based on the results given in the previous section, we find that the number of galactic neutrinos ($\nu_e + \bar{\nu}_e$) observed in one year at $E \gtrsim 10$ TeV in a $10^{10}$ ton DUMAND detector is calculated to be 45 if one used a primary cosmic ray spectrum $dJ/dE \propto E^{-2.67}$. However, adopting the steeper primary spectrum obtained in more recent work, a more conservative event rate is obtained. The primary spectrum given in Ref. 14, which is consistent with the data in Ref.'s 15 and 26, will be adopted here, yielding a galactic event rate of $\sim 18$/yr above $10$ TeV. At $1$ TeV, the event rate is $\sim 16$ times higher.

About 45% of the expected galactic events come from a galactic central region $+8^\circ$ in latitude and $+50^\circ$ in longitude. The prompt atmospheric neutrino fluxes for $R = 10^{-5}$ and $R = 10^{-3}$ are given in Figure 7. The atmospheric $\pi$ and K decay fluxes are given in Ref. 26. The mean atmospheric neutrino flux from $\pi$ and K decay is $\sim 0.5$ of the horizontal flux at 1 TeV and $\sim 0.3$ at 10 TeV.

The event rates for a $10^9$ ton detector as given in Ref. 34 are shown in Table 2. It can be seen that the inner region of the galaxy may be detectable above atmospheric background fluctuations with observing runs of 4 years or longer.

6.2 Observability of the Nearby Quasar 3C273

In considering neutrino astronomy of extragalactic point sources, the quasar 3C273 provides an excellent subject for consideration because of its closeness and prominence among quasars and because it is the only known extragalactic source of 100 MeV $\gamma$-rays. Thus, if the $\gamma$-radiation from 3C273 is the result of meson production in cosmic-ray interactions...
Table 2. Observability of Galactic Central Region

<table>
<thead>
<tr>
<th>Energy (TeV) (R=10^-3)</th>
<th>N_prompt</th>
<th>Number of Atmospheric Neutrino Events/yr.</th>
<th>Number of ν's from G.C./yr.</th>
<th>c's of G.C. Events Above Atm. Bkgd. (4 yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_μ+ν_μ</td>
<td>&gt; 1</td>
<td>380</td>
<td>17,600</td>
<td>130</td>
</tr>
<tr>
<td>10</td>
<td>23</td>
<td>120</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>ν_e+ν_μ</td>
<td>&gt; 1</td>
<td>380</td>
<td>790</td>
<td>34</td>
</tr>
<tr>
<td>10</td>
<td>23</td>
<td>4</td>
<td>5.2</td>
<td>4</td>
</tr>
<tr>
<td>ν_μν_μ</td>
<td>&gt; 1</td>
<td>38</td>
<td>17,600</td>
<td>130</td>
</tr>
<tr>
<td>10</td>
<td>2.3</td>
<td>120</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>ν_eν_e</td>
<td>&gt; 1</td>
<td>38</td>
<td>790</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>2.3</td>
<td>4</td>
<td>2.5</td>
<td>4</td>
</tr>
</tbody>
</table>

In the source, either through π^- decay or the bremsstrahlung of electrons from π^- decay, the 100 MeV neutrino flux from 3C273 may be comparable to the 6x10^-17 cm^-2 s^-1 γ-ray flux observed by the COS-B satellite for this source.

Taking the resolution element for neutrinos with E>1 TeV from DUMAND to be ΔΩ = 3x10^-4 sr, the atmospheric neutrino event rate in ΔΩ is expected to be N/yr above 1 TeV. Thus, a 3σ signal, certainly the absolute minimum for observability of a point source, would be N/yr. For a source with a differential energy spectrum \(\propto E^{-2.7}\), this would correspond to a \(>1\) TeV neutrino flux of \(6x10^{-12}\) cm^-2 s^-1. If the integral ν-spectrum from 3C273 follows an \(E^{-1.7}\) power law from a value of \(6x10^{-7}\) cm^-2 s^-1 at 100 MeV, the resultant flux above 1 TeV would be \(10^{-12}\) cm^-2 s^-1, a factor of 60 below the level of detectability. Indeed, the integral spectrum would have to be flatter than \(E^{-1.25}\) for detectability, which seems unlikely since the photon spectrum appears to steepen between the x-ray and γ-ray range. The case for detectability of other steady extragalactic sources whose 100 MeV

Fig. 8 - Fluxes of atmospheric electron-neutrinos from π and K decay and from prompt decay as compared with the diffuse flux from the inner galaxy.
\( \gamma \)-ray flux remains below present satellite detectability seems even more hopeless with one possible loophole. It is possible that cosmic rays could be produced in the core regions of quasars, there producing \( \nu \)'s while the \( \gamma \)-rays are absorbed in optically thick regions. In that case, the producing regions must be much smaller than the \( \lesssim 0.1 \) pc size of the \( x \)-ray producing region since the column density in the \( x \)-ray producing regions is \( < 4.5 \times 10^{21} \text{cm}^{-2} \) at the 90% confidence level \( ^{48} \) less than 4 orders of magnitude below the \( \gamma \)-ray mean-free-path. It also appears that the \( \gamma \)-ray emission from quasars is more likely electromagnetic in origin \( ^{47,48} \), and therefore unconnected to \( \gamma \)-production. It would therefore be of extraordinary interest if neutrinos from 3C273 were detected, as it would reveal entirely new information about the fundamental nature of quasars. But observability is uncertain at best in terms of present theoretical ideas.

7. Cosmological Neutrino Background

Following a suggestion \( ^{49} \) that a high-redshift cosmological origin of the high energy cosmic radiation could explain the steepening of its spectrum above \( \sim 10^8 \) GeV, a cascade origin of the cosmic \( \gamma \)-ray background radiation was also suggested \( ^{50} \), followed by suggestions that such a burst of cosmic ray production in the distant past would result in copious neutrino fluxes \( ^{31} \). It should, however, be noted that photopion production of neutrinos in an early intergalactic (or pregalactic) medium is limited by observational constraints on the associated \( \gamma \)-ray background radiation \( ^7 \). These constraints therefore call into question burst production or "bright phase" models. The "\( p\bar{p} \)" limit from the \( \gamma \)-ray observations is shown in Fig. 5 marked PCR(UL) (see section 3). The \( p\bar{p} \) limit is not related to the \( x \)-ray background as previously suggested \( ^{51} \) because the \( x \)-ray background cannot be related to photopion production since the shape of the \( \gamma \)-ray background has the form \( \propto E^{-3} \) above 10 MeV \( ^{29} \) whereas the photopion model would give a spectrum of the form \( ^{50} \propto E^{-2} \). Furthermore the model on which the high-redshift calculations are based implies a \( \gamma \)-ray background flux above that observed unless the mean intergalactic gas density at present is \( \lesssim 10^{-40} \text{cm}^{-3} \) (based on the discussion in Ref. 23 with updated \( \gamma \)-ray data), and unless galaxy formation occurred at an extremely efficient rate at redshifts \( \geq 15 \). These assumptions create
problems of compatibility with recent x-ray observations of intergalactic gas in galaxy clusters and with radio and optical galaxy observations.

The remaining way of producing a high flux of neutrinos at high redshifts would be in the cores of compact astrophysical objects (quasars, Seyfert galaxies, etc.). Compatibility with other observations would be maintained provided that a) the co-produced γ-radiation is absorbed in the sources, and b) the cosmic rays also do not escape the sources and produce intergalactic γ-ray emission. The difficulties with such models have already been discussed in section 6.2.

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References

### Extraterrestrial High Energy Neutrino Fluxes

**Abstract**

Using the most recent cosmic ray spectra up to $2 \times 10^{20}$ eV, production spectra of high energy $\nu$'s from cosmic ray interactions with interstellar gas, and extra-galactic ultrahigh energy cosmic ray interactions with 3K universal background photons are presented and discussed. Estimates of fluxes from cosmic diffuse sources are made using the generic relationship between secondary $\gamma$'s and $\nu$'s and using recent cosmic $\gamma$-ray satellite observations. Those observations in particular can provide important upper limits on cosmological $\nu$'s which are much smaller than some previous upper limits. We then give a quantitative estimate of the observability above the atmospheric background of 1-10 TeV $\nu$'s from the inner Galaxy for a DUMAND type detector. The atmospheric background fluxes used for this calculation include the contribution from charmed meson decay which can play a substantial role, particularly above 10 TeV. Event rates were estimated using a quark-parton model of the nucleon and the Weinberg-Salam model of weak interactions with $\sin^2 \theta_W = 0.2$ in calculating the $\nu N$ interaction cross section. Electron $\nu$'s may be marginally observable with such a system, giving a 4-5$\sigma$ signal over a four year observing time. (For $\nu_\mu$'s the signal would be $\sim 2\sigma$.)

**Key Words (Selected by Author(s))**

Cosmic rays, neutrinos, galaxy, quasar, charm, weak interactions