MUON AND NEUTRINO FLUXES

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Abstract. We report the result of a new calculation of the atmospheric muon and neutrino fluxes and the energy spectrum of muon-neutrinos produced in individual extensive air showers (EAS) initiated by proton and γ-ray primaries. We also examine the possibility of detecting atmospheric ν_μ's due to γ-rays from sources.

1. *INTRODUCTION.* Interactions of ~1 GeV neutrinos can mimic nucleon decay events and it is therefore important to know the atmospheric neutrino flux in order to calculate the expected rate of background events in nucleon decay experiments. With the development of large nucleon decay detectors this topic has received much interest over the past few years (Gaisser *et al.*, 1983a,b; Dar 1983). These large detectors can also be used for other purposes, however. Their large masses make them good neutrino detectors allowing searches for neutrinos from bright extra-terrestrial sources. Here again an accurate knowledge of the atmospheric neutrino background due to cosmic rays is important.

The detection of UHE γ-rays from Cygnus X-3 (Samorski and Stamm, 1983; Lloyd-Evans *et al.*, 1983), Vela X-1 (Protheroe *et al.*, 1984) and LMC X-4 (Protheroe and Clay, 1985) has added further impetus to the neutrino observations as it is usually considered that a neutrino signal would almost certainly suggest a π^0-decay origin for the γ-rays. Gaisser and Stanev (1985a,b) have recently calculated the expected ν_μ flux and light curve for Cygnus X-3 on this basis together with the response of deep detectors to extraterrestrial neutrinos.

Here, we report the results of a new calculation of the sea level atmospheric muon and neutrino fluxes. We have also calculated the energy spectrum of ν_μ's in individual EAS initiated by primary protons and γ-rays to test whether atmospheric neutrinos from γ-ray initiated EAS could be detected with existing detectors.

2. *THE CALCULATION.* The simulation procedure was identical to that used in our earlier work (Edwards *et al.*, 1985) and consisted of numerical solution of the following coupled equations (see e.g. Gaisser *et al.*, 1978):

$$\frac{\partial N_i(E,x)}{\partial x} = - N_i(E,x)\left[\frac{1}{x_i(E)} + \frac{(dh/dx)}{(cE/m_i)\tau_i}\right] + \frac{\partial}{\partial E}\left[N_i(E,x)(dE/dx)_i\right]$$

$$+ \sum_j \int_E^\infty \left[\frac{F_{ji}(E,E')}{E}\,\frac{N_j(E',x)}{x_j(E')}\right]dE', \qquad (1)$$

where N_i is the energy distribution of particles of type i at depth x; x_i is the mean interaction length, m_i is the rest mass, τ_i is the mean decay time, and $(dE/dx)_i$ is the mean ionization energy loss rate of particles of type i; and $F_{ij}(E,E')dE/E$ is the probability of a particle of type j and energy E' producing a particle of type i and energy E to E+dE per interaction. The particles considered in the simulation were: nucleons, charged pions, charged and neutral kaons, muons and both muon and electron neutrinos (by "neutrinos" we include anti-neutrinos).

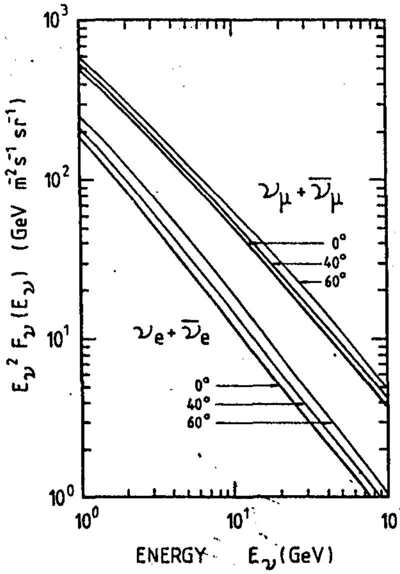

Fig. 1. Sea level atmospheric neutrino flux at 0°, 40° and 60° to the zenith.

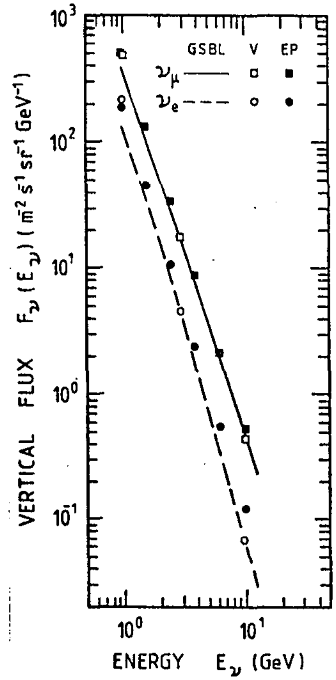

Fig. 2. Vertical neutrino flux from present work (EP) compared with the predictions of Volkova (1980) (V) and Gaisser *et al*. (1983a,b) (GSBL).

The model of inclusive particle production in proton-air nucleus interactions used in the simulations is that described by Gaisser, Protheroe and Stanev (1983). The nucleon-air nucleus interaction length used was that given by Ellsworth *et al*. (1982). The pion and kaon-air nucleus interaction lengths were suitably scaled from this (Hillas, 1979).

The primary cosmic ray nucleon flux used was based on the results of satellite and balloon-borne detectors (Simpson *et al*. 1983; Ryan *et al*. 1972; Gregory *et al*. 1981; Simon *et al*. 1980; Juliusson *et al*. 1983; Sood 1983) and the superposition model.

3. ***RESULTS***. First we present our results on the flux of atmospheric muons and neutrinos. The calculated sea level neutrino flux is shown in Fig. 1 for a number of zenith angles and is seen to increase with increasing zenith angle (i.e. atmospheric thickness). We have compared our calculated neutrino fluxes with previous results. Fig. 2 shows the good agreement found with the vertical flux calculated by Gaisser *et al*. (1983a,b) and Volkova (1980). The results of Tam and Young (1969) (not plotted) are similarly in agreement.

The vertical muon flux we calculate is plotted in Fig. 3 where it is compared with the experimetal results obtained by Mitsui *et al*. (1983) and Allkofer *et al*. (1971) and found to

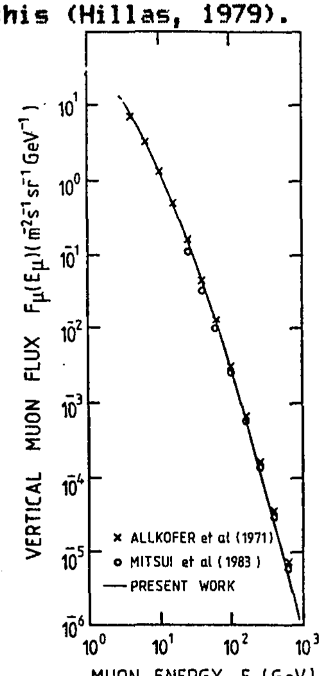

Fig. 3. Calculated vertical muon flux compared with recent observations.

be in good agreement.

We turn now to neutrinos produced in individual cosmic ray and γ-ray initiated EAS. In Fig. 4 we show the differential energy spectra of ν_μs produced in individual EAS divided by the primary energy. Over the $10^{1[illegible]}$ – $10^{1[illegible]}$ eV primary energy range, the ν_μ spectrum in γ-ray initiated EAS is ~10 to 100 times lower than in proton initiated EAS. Also, the number of neutrinos divided by primary energy decreases with increasing primary energy in cosmic ray EAS but is approximately independent of primary energy for γ-ray initiated EAS. This behaviour is similar to that of muons in cosmic ray and γ-ray initiated EAS (Edwards *et al.*, 1985).

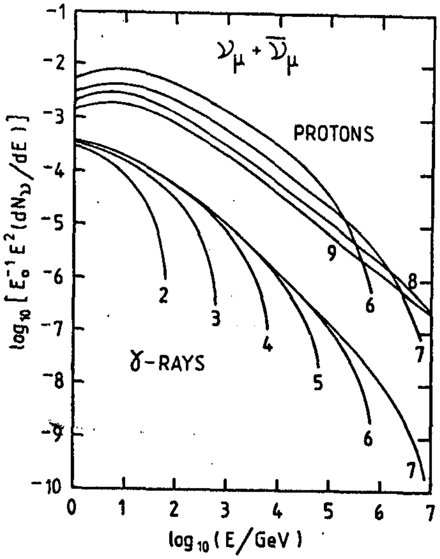

Fig. 4. Differential energy spectrum of muon neutrinos in proton and γ-ray initiated EAS divided by primary energy, E_o. (Numbers attached to the curves are $log_{10}[E_o/GeV]$).

4. *DISCUSSION*. Recently Gaisser and Stanev (1985a) have calculated the expected ν_μ flux and light curve of Cygnus X-3 assuming it is due to protons produced near the neutron star interacting in the atmosphere of its companion to produce a mini-EAS in in the star's atmosphere. Cocconi (1985) has also suggested that LMC X-4, being a bright Southern UHE γ-ray source, would be a good neutrino source candidate for study by Northern observers.

It is possible (although we consider it unlikely) that the γ-rays from Cygnus X-3 are due to interactions of electrons accelerated to extremely high energies. If this were the case, we would expect no neutrinos from the source. Observation of neutrinos from Cygnus X-3 would then indicate that the γ-rays were almost certainly due to interactions of high energy protons. Atmospheric neutrinos due to γ-rays from Cygnus X-3 might also be detectable, however. If this was so, then such a conclusion would be invalid although it may be possible to distinguish the two origins through the light curves which would be different in each case. Here, we calculate the differential ν_μ flux due to γ-rays from Cygnus X-3 by convolving the ν_μ spectra in γ-ray initiated

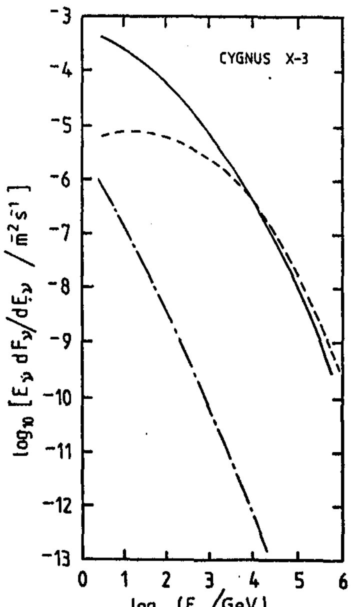

Fig. 5. Expected flux of atmospheric ν_μs due to γ-rays from Cygnus X-3 (dot-dash line) compared with the flux expected directly from the source (solid and dashed lines) under two different assumptions (Gaisser and Stanev, 1985a).

EAS of Fig. 4 with the γ-ray spectrum of the source:

$$N(E) = 4.5\times10^{-4}(E/GeV)^{-2} \text{ (photons m}^{-2}\text{ s}^{-1}\text{ GeV}^{-1}). \qquad (2)$$

This is based on the integral flux reported by Lloyd-Evans *et al.* (1983). The result is shown in Fig. 5 where it is compared with the expected ν_μ flux due directly to the source as calculated by Gaisser and Stanev under two different assumptions. At 1 TeV the atmospheric ν_μ flux is $\sim10^{8}$ lower than that due directly to the source and would be considerably below current detector sensitivities (Stenger 1985).

5. *CONCLUSIONS.* Our calculated atmospheric muon flux is in good agreement with observations. The calculated neutrino flux is in agreement with other recent predictions. We support the view that a neutrino observation of a UHE γ-ray source would be strong evidence that the UHE γ-rays and neutrinos result from high energy interactions of protons or nuclei.

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