THE ASTROPHYSICAL JOURNAL, **281**:L9–L12, 1984 June 1

LIMITS ON ASTROPHYSICAL ν_e FLUX AT $E_\nu > 10^{19}$ eV

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Received 1983 November 28; accepted 1984 February 16

ABSTRACT

We report on a search for upward-going extensive air showers using the University of Utah Fly's Eye detector. No events have been found in 3.9×10^6 s of running time. The resultant ν flux limit at 10^{20} eV varies from 5.8×10^{-16} ν cm^{-2} s^{-1} sr^{-1} to 3.0×10^{-14} ν cm^{-2} s^{-1} sr^{-1} for σ_ν between 10^{-33} cm^2 and 10^{-32} cm^2. We also present flux limits for larger σ_ν using near-horizontal events originating in the atmosphere. The implications of the flux limits at $E_\nu > 10^{20}$ eV are discussed.

Subject headings: cosmic background radiation — cosmology — early universe — neutrinos

I. INTRODUCTION

We report on a search for neutrino-induced extensive air showers in the energy range greater than 10^{19} eV. There may be a number of mechanisms for the production of such neutrinos. The most theoretically clean predictions concern the interaction of the primary cosmic-ray protons at energies of approximately 10^{20} eV with 2.7 K blackbody photons (Stecker 1968; Berezinsky and Zatsepin 1970; Margolis, Schramm, and Silverberg 1978; Hill and Schramm 1983). In the rest frame of the proton, this energy corresponds to the onset of $N^*(1238)$ photoproduction by approximately 300 MeV c^{-1} photons. The ν_μ's and ν_e's are then produced from the subsequent decay of π's and μ's in a ratio of 2 to 1. The main inputs to these calculations are: (*a*) the universality and blackbody spectral shape of the 2.7 K radiation; (*b*) the universality and spectral shape of cosmic-ray production processes out to redshifts of $z \sim 1$; (*c*) the approximately 300 MeV c^{-1} photoproduction cross section; (*d*) π and μ decay kinematics; and (*e*) a value for the intergalactic magnetic field of approximately 10^{-9} gauss. Since (*c*) and (*d*) are well known, observation or nonobservation of the neutrino flux tests issues (*a*), (*b*), and (*e*). The resultant calculations lead to a neutrino flux of the order of 10^{-17} ν cm^{-2} s^{-1} sr^{-1} for neutrino energies between 10^{19} and 10^{20} eV. The uncertainties in the calculation, assuming universality is correct, are approximately one order of magnitude.

Above energies of 10^{20} eV, production mechanisms for ν's are completely speculative. Nevertheless, the existence of such a flux, presumably due to astrophysical objects with very intense neutrino emissions, would be quite interesting since its magnitude might be sensitive to the value of the neutrino mass and might provide evidence for the existence of a relic neutrino background, as suggested by Weiler (1982). At neutrino energies of 10^{21} eV or larger, the $\nu\bar{\nu} \rightarrow Z^\circ$ reaction off relic neutrinos is believed to generate a finite mean free path for neutrinos from highly redshifted sources and hence produce a dip in the neutrino transmission probability. The dip will occur at $10^{23} < E_\nu < 10^{24}$ eV for massless neutrinos and at $E_\nu \sim 10^{20}$–10^{21} eV for massive (nonrelativistic) relic neutrinos.

We search for such events in conjunction with the normal operation of the University of Utah Fly's Eye detector. The signature distinguishing such events from hadronically induced extensive air showers (EAS) is their deeply penetrating nature. In the following, we use the Earth as well as the atmosphere as both a hadron filter and a neutrino target (Sokolsky 1983; Cady *et al.* 1984).

II. DETECTOR

The Fly's Eye detector has been described in detail elsewhere (Cady *et al.* 1982). Briefly, the detector collects light from nitrogen fluorescence, produced by EAS in their passage through the atmosphere, in an array of 880 phototubes spanning the entire hemisphere of the sky. Analysis of timing and pulse-height information allows the determination of arrival direction, total energy, shower development, and position of shower maximum for EAS with energies greater than 10^{17} eV. For energies of about 10^{20} eV, the effective volume of the atmosphere over which EAS can be detected is roughly a cylinder about 15 km high by about 20 km in radius. To fully reconstruct an EAS with good zenith angle accuracy ($\Delta\theta \leq \pm 10^\circ$), a shower must have a track length projected on the celestial sphere of greater than 50° and an impact parameter relative to the Fly's Eye greater than 1.5 km. For energies greater than 10^{20} eV, the detection volume increases, but the greater than 50° track length requirement reduces reconstruction efficiency beyond 20 km.

III. SEARCH PHILOSOPHY

The Weinberg-Salam (W-S) model of weak interactions predicts σ_ν at 10^{19} eV to be approximately 10^{-33} cm^2. Corrections for QCD effects may make this cross section somewhat larger (Andreyev, Berezinsky, and Smirnov 1979). If 10^{-33} cm$^2 < \sigma_\nu < 10^{-32}$ cm^2, the spherical shape of the Earth allows a significant ν flux to pass through. As $\sigma_\nu \rightarrow 10^{-32}$ cm^2, only the nearly horizontal ν flux has an appreciable probability of reaching the surface. In this cross section interval, we search for ν_e events because the electron from the ν_e interaction will carry most of the neutrino energy ($E_e/E_\nu \rightarrow 1$ at these energies in the W-S model). Moreover, it will have an effective radiation length increased by many orders of magnitude over Bethe-Heitler due to the turn-on of the Landau-Pomeranchuk-Migdal (LPM) effect (Landau and Pomeranchuk 1953; Migdal 1957). This allows us to detect electron showers from ν interactions hundreds of meters below the surface of the Earth and increases the available target mass. Note that since the LPM effect depends on density, showers entering the atmosphere from the Earth's crust develop with near-normal cross sections. If $\sigma_\nu > 10^{-32}$ cm^2, near-horizontal, downward ($80° < \theta_z < 90°$) events can be used to search for ν candidates. Such events, originating in the detection volume described above, must traverse more than 5000 g cm^{-2} of atmosphere before interacting, thus ensuring their weakly interacting nature. We again consider only ν_e events because the resultant electron takes most of the incident ν_e energy and is visible over approximately the same detection area as for upward showers.

IV. UPWARD SHOWER CALCULATION

The flux limit based on upward showers depends on how deeply into the Earth's crust an event can occur and still yield a detectable EAS. We have calculated the dependence of $N_{\max}$, the number of particles at shower maximum, and $t_{\max}$, the depth of shower maximum in the atmosphere, on the depth of origin into the Earth's crust of the electron for different electron energies in a Monte Carlo program. The calculations are described in detail by Sokolsky and Mizumoto (1984). Briefly, we use the LPM brehmsstrahlung and pair-production cross sections as calculated by Migdal (1957) and incorporate them into a standard electromagnetic shower development Monte Carlo under "approximation A" (no Compton scattering or ionization loss taken into account). The results of the calculation at $E_e \leq 10^{15}$ eV agree very well with other recent calculations in homogeneous material (e.g., Pb). These, in turn, agree with existing experimental data (Konishi, Misaki and Fujimaki 1978; Bourdeau, Capdevielle, and Procureur 1981; Stanev *et al.* 1982). Electrons were followed to a threshold energy of 100 GeV. The $N_{\max}$ and $t_{\max}$ distributions are shown in Figures 1 and 2. The results indicate that electrons with $E = 10^{19}$ eV can be detected with good efficiency down to 100 m of crust while $E = 10^{20}$ eV electrons can be seen to approximately 300 m, and 10^{21} eV electrons to roughly 1200 m. Over most of this range of depth, the electromagnetic shower visible in the atmosphere is essentially indistinguishable in shape (shower size versus g cm^{-2}) from a hadronic shower with the same effective energy. This allows us to calculate the detection efficiency for such showers once they emerge into the atmosphere by using our detection efficiency programs which have been cross-checked with data from hadronic cosmic-ray EAS. We note, for instance, that for $E_\nu = 10^{20}$ eV, the average detection efficiency over a 20 km radius for upward event is about 60%.

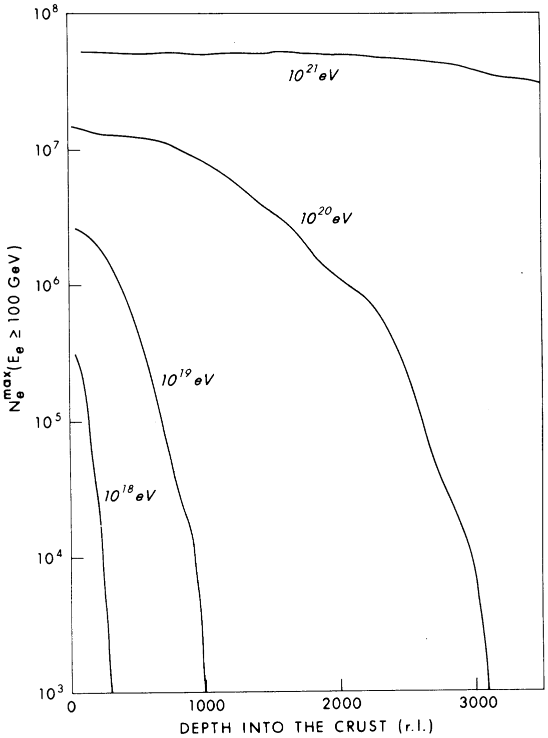

FIG. 1.—Dependence of $N_e^{\max}$, the number of electrons at shower maximum in the atmosphere, on depth into the Earth's crust of neutrino interaction. The radiation length of the crust is assumed to be 11.4 cm. The curves are results of averaging over 100 showers. The question of fluctuations will be addressed in a future paper (Sokolsky and Mitzumoto 1984).

V. UPWARD EVENT RESULTS

Figure 3 gives the distribution in zenith angle of all EAS events with greater than 50° track length and impact parameter greater than 1.5 km for 3.9×10^6 s of run time. Although we expect no hadronically induced events with zenith angles $\geq 80°$, finite angular resolution folded into a falling spectrum inevitably generates such events. We observe no events with $\theta_z > 90°$. Table 1 gives the resulting neutrino flux limits as a function of σ_ν and E_ν. Note that in this cross section interval, the limit, before acceptance correction, is almost independent of cross section. For a near-horizontal ν flux, decreases in the flux due to increasing interaction length in the Earth are compensated for by an increasing probability of the ν interacting in the visible detection length below the Earth's surface. The decrease in sensitivity as $\sigma_\nu \rightarrow 10^{-32}$ cm^2 is due to the nearly horizontal distribution of such events.

VI. DOWNWARD EVENT RESULTS

Figure 3 shows six events with $80° < \theta_z < 90°$. However, analyis of the energies of these events indicates that none have $E \geq 10^{19}$ eV, and hence they are most likely due to spill-down of ordinary cosmic rays. The limits on neutrino flux as a function of σ_ν for downward events are given in Table 2. The limits at 10^{20} eV are also limits for $E > 10^{20}$ eV.

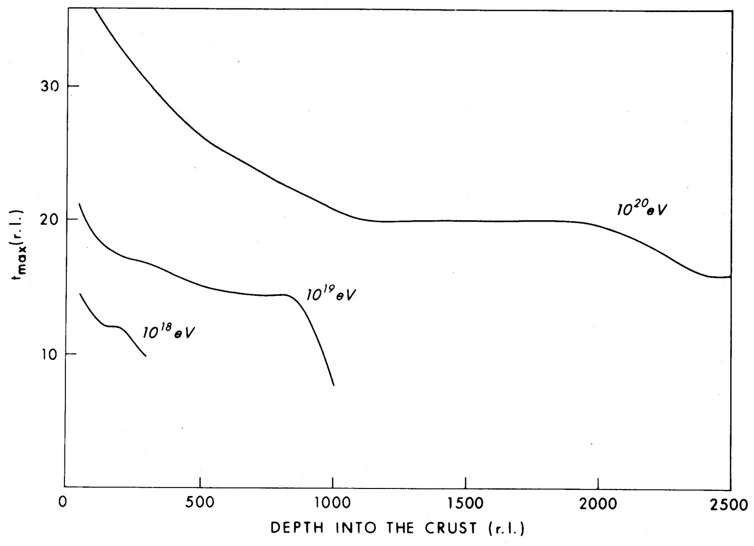

FIG. 2.—Dependence of $t_{\max}$, the position of the shower maximum in the atmosphere, on depth into the Earth's crust of the neutrino interaction.

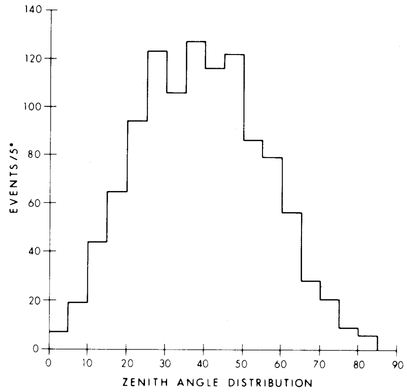

FIG. 3.—Zenith angular distribution for all events with impact parameter greater than 1.5 km and track length greater than 50°.

TABLE 1

FLUX LIMITS BASED ON UPWARD EVENTS (in ν cm^{-2} s^{-1} sr^{-1})

σ_ν (cm^2)	$E_\nu = 10^{19}$ eV	$E_\nu = 10^{20}$ eV	$E_\nu = 10^{21}$ eV
1×10^{-33} ...	6.2×10^{-15}	5.8×10^{-16}	9.0×10^{-17}
3×10^{-33} ...	1.2×10^{-14}	1.1×10^{-15}	1.7×10^{-16}
5×10^{-33} ...	3.5×10^{-14}	3.4×10^{-15}	5.0×10^{-16}
1×10^{-32} ...	3.2×10^{-13}	3.0×10^{-14}	4.6×10^{-15}

TABLE 2

FLUX LIMITS BASED ON DOWNWARD EVENTS (in ν cm^{-2} s^{-1} sr^{-1})

σ_ν (cm^2)	$E_\nu = 10^{19}$ eV	$E_\nu = 10^{20}$ eV
1×10^{-33} ...	1.6×10^{-13}	5.8×10^{-14}
1×10^{-32} ...	1.6×10^{-14}	5.8×10^{-15}
1×10^{-31} ...	1.6×10^{-15}	5.8×10^{-16}
1×10^{-30} ...	1.6×10^{-16}	5.8×10^{-17}
1×10^{-29} ...	1.6×10^{-17}	5.8×10^{-18}

VII. CONCLUSIONS

We find the flux limit for $\sigma_\nu = 10^{-33}$ cm^2 at 10^{20} eV is 5.8×10^{-16} ν cm^{-2} s^{-1} sr^{-1}. This is the first significant flux limit measurement in this energy range. We believe that better understanding of the detector response to showers with track lengths less than 50° and distances beyond 20 km, several more years of running time, and improvements in detector sensitivity will allow us to push this limit down to the theoretical prediction of approximately 10^{-17} ν cm^{-2} s^{-1} sr^{-1}. We note that observations of neutrinos at the above level would indicate the presence of an intergalactic B field of the order of 10^{-9} gauss (Hill and Schramm 1983) and would confirm the universality of both the 2.7 K radiation and the primary cosmic-ray spectrum. We also note that our present results imply that ν fluxes continue to be very small at energies greater than 10^{20} eV.

We thank the National Science Foundation for support of this research under grant 8201089.

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