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AN UPPER LIMIT ON THE FLUX OF EXTRATERRESTRIAL NEUTRINOS

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ABSTRACT

A search is made for neutrino-induced muons from Cyg X-3, Her X-1, LMC X-4, Vela X-1, Geminga (= 2CG 195+4), the Crab Nebula, Cen A, 3C 273, SS 433, and the center of our Galaxy using a large underground ring-imaging water Cerenkov detector. For this study, the detector is used to measure the track direction of upward-going muons (energy > 2 GeV) produced by neutrino interactions in the surrounding rock. Over a period of 1.5 yr (344 live days), 172 such events were recorded, corresponding to a measured flux of $2.41 \pm 0.21 \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1} for zenith angles greater than 98°. This overall rate is consistent with that expected from ordinary cosmic-ray interactions with Earth's atmosphere, which is calculated to be 2.36 ± 0.12 statistical $\pm$ 0.35 systematic $\times 10^{-13}$ cm^{-2} sr^{-1}. In addition, it is shown that the arrival directions of these muons show no significant correlation with any of the above-listed objects. Upper limits are placed on the incident neutrino flux and luminosity of each object for assumed source spectral indices of 2.3 and 3.0 based on detailed computer simulations of the detector's effective area, efficiency, and energy threshold.

Subject headings: cosmic rays: general — neutrinos — X-rays: sources

I. INTRODUCTION

Photons and neutrinos are the only known particles available for directional astronomy over interstellar distances. The paths of charged particles are distorted by the Galactic magnetic field, and other known neutral particles are unstable and would decay before reaching Earth. Since neutrinos can penetrate large amounts of matter, their detection from astrophysical sources would provide information on processes occurring in the interior of such objects. It has been suggested by Stecker (1979) and Berezinsky (1979) that the center of our own Galaxy may be a copious source of energetic neutrinos. Eichler (1978) and Berezinsky and Castagnoli (1985) have shown that conditions in regions surrounding young pulsars or pulsars orbiting massive companions may be optimal for neutrino production, though Berezinsky's estimate of the neutrino luminosities of such objects places them below the detectable range of present-generation underground neutrino detectors. Cocconi (1985) and Brecher and Chanmugam (1985), however, have calculated that objects such as LMC X-4 and Cyg X-3 may be just detectable in a sufficiently large detector similar to the one used here.

II. OBSERVATIONS AND RESULTS

The Irvine-Michigan-Brookhaven (IMB) detector is an 8 kilotonne underground water Cerenkov detector located at a depth of 600 m (1570 m water equivalent) in the Morton-Thiokol salt mine in Fairport, Ohio (latitude $41^{\circ}\!.72$ N, longitude $81^{\circ}\!.27$ W). It consists of an 18 m × 17 m × 22.5 m tank of water surrounded on all six faces by 2048 5 inch (12.6 cm) hemispherical photomultiplier tubes (PMTs) facing inward. The PMTs record the intensity and relative time of arrival of the Cerenkov light produced by charged particles with $v/c > 0.75$ traversing the water in the tank. This information is stored on magnetic tape and is later used to reconstruct the particle track. The IMB detector is the largest of several underground detectors built chiefly to search for nucleon decay. Detailed information on the design, construction, and calibration of the detector can be found in Svoboda (1985) and Bionta *et al.* (1983).

Since muon neutrinos arriving from an astrophysical source below the detector horizon line can penetrate kilometers of rock before they interact to produce muons, the signature of such a source would be a number of upward-going tracks which point within a few degrees of the source position. The exact angle between the daughter muon and the parent neutrino is mostly a function of their energy. This is discussed in § III. When the source is above the horizon, the neutrino-induced muon tracks are lost in the background of downward-going muon tracks from cosmic-ray interactions in the upper atmosphere; thus neutrino sources can only be observed when they are below the horizon. Of course, when they are below the horizon there is still a background of muons from atmospherically produced neutrinos, but this is six orders of magnitude

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less than the down-going muon flux, and the directional distribution of such tracks should be roughly isotropic.

Between 1983 February 7 and 1984 July 4, 344 observational days were logged and $\sim 10^8$ particle tracks were registered. The vast majority of these tracks are due to one or more particles entering the detector from above and exiting near the bottom. The rate (2.7 s^{-1}) and zenith angle θ distribution ($\propto \cos^3 \theta$) are consistent with those expected from secondary cosmic-ray muons.

About once per day, the detector records an event which originates inside the detector volume. The rate and zenith angle distribution (approximately isotropic) of these events has been discussed in detail by Park *et al.* (1985) and found to be consistent with that expected from the interaction of secondary cosmic-ray neutrinos with energies less than ~ 5 GeV.

Approximately once every 2 days, a track image is recorded which enters the detector from below the horizon line, i.e., from $\theta > 90°$. A total of 172 events of this type were detected over the observation period. Details on the data sample search and track reconstruction of these events may be found in Svoboda (1985). Figure 1 shows the arrival directions of these events in equatorial coordinates.

III. DISCUSSION

The majority of the 172 upward-going muon events found are due to atmospheric neutrino interactions. This conclusion is based on a comparison of the observed upward-going muon flux with a computer calculation of that expected from atmospherically produced neutrinos. The calculation is done using a Monte Carlo computer program which is based on the high-energy neutrino flux estimates of Volkova (1980), a standard scaling model of muon neutrino interactions, and a computer algorithm which simulates the propagation of muons through the detector and surrounding rock. The output of the program consists of simulated data events representing 1000 live days of detector operation. Passing these computer-generated events through the same reduction and reconstruction used on the actual data provides estimates of the muon energy threshold (2 GeV), efficiency (83%), angular resolution (mean error 3°.5), and effective area (390 m^2). The event rate of upward-going neutrino-induced muons is predicted to be 0.435 events day^{-1}. This rate has a statistical error of 0.021 events day^{-1} from the Monte Carlo and is assigned a systematic error of 0.065 events day^{-1} due to uncertainties in the knowledge of the atmospheric neutrino spectrum.

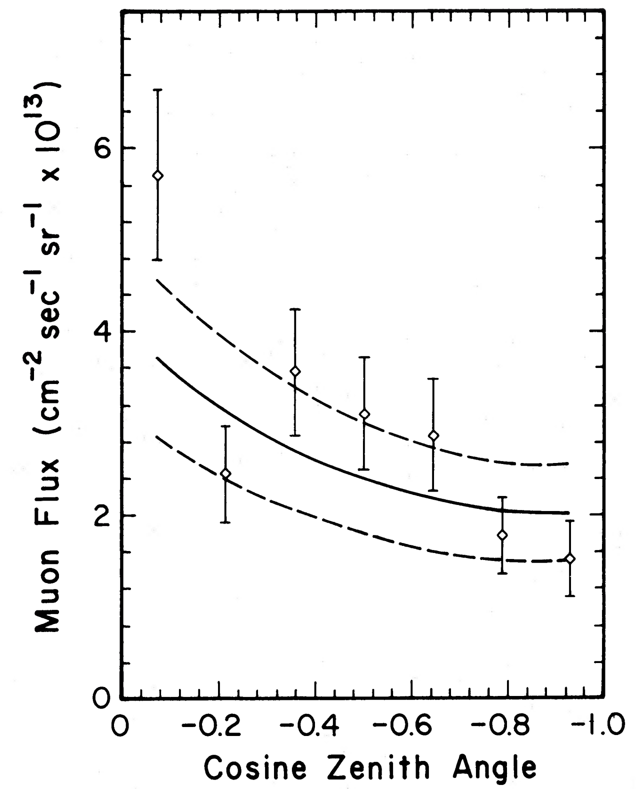

FIG. 2.—Measured flux of upward-going muons as a function of the zenith angle. *Solid line*, expected flux due to atmospheric neutrino interactions; *dashed lines*, estimated error.

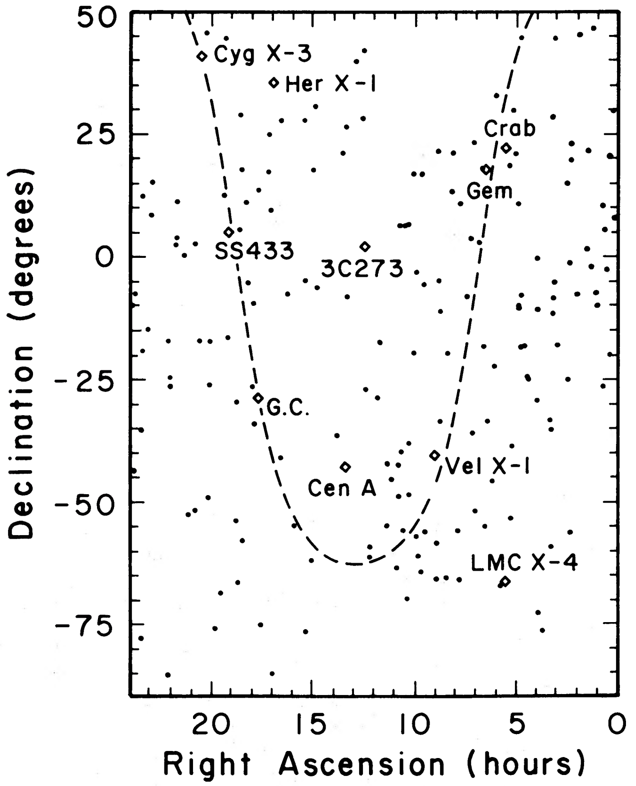

FIG. 1.—Arrival directions of the 172 upward-going muon events in equatorial coordinates. *Dashed line*, plane of our Galaxy.

Six of the 172 events were not found by the data reduction algorithms but were recovered by other routines used to study upward-going muon events in a search for evidence of neutrino instability. This search is described in Casper (1985). These events must be subtracted from the data sample when calculating the observed absolute upward-going muon flux using the efficiency from the simulation results.

Figure 2 shows the measured flux based on the original 166 events as well as the flux predicted by the simulation as a function of zenith angle. They are seen to be in reasonable good agreement except for the angular bin nearest the horizon. This bin probably contains some contamination from atmospheric muons of very high energy or which have scattered in the rock.

The absolute flux values shown in Figure 2 were calculated by comparing the observed number of events in each angular bin to the number of Monte Carlo events in the bin and scaling

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the simulated flux by the ratio of 344 real live days to 1000 simulated live days.

The total flux integrated over the detector aperture is 2.81 ± 0.22 statistical × 10^{-13} cm^{-2} s^{-1} sr^{-1} compared to the expected value of 2.55 ± 0.12 statistical ± 0.38 systematic × 10^{-13} cm^{-2} s^{-1} sr^{-1}. Leaving out the first bin (which corresponds to an angular cut of $\sim 98°$), the measured flux is 2.41 ± 0.21 statistical × 10^{-1} cm^{-2} s^{-1} sr^{-1} compared to an expected value of 2.36 ± 0.12 statistical ± 0.35 systematic. Thus the total flux is consistent with being due entirely to atmospheric neutrinos, once one gets away from atmospheric muon contamination. Using the method of Protheroe (1984), a 90% confidence level (c.l.) upper limit of 4.6×10^{-14} cm^{-2} s^{-1} sr^{-1} is placed on the total contribution to the observed flux from nonatmospheric sources at 98°. This limit does not take into account possible systematic errors in the estimated background flux.

In order to determine whether the track arrival directions shown in Figure 1 are correlated with some extraterrestrial source, it is first necessary to know what the angular distribution of tracks about a neutrino point source would look like in the IMB detector. Due to the detector's angular resolution and the interaction scattering angle from the incident neutrino, the muons would not be expected to point directly to the source.

TABLE 1

RESULTS OF SOURCE SEARCH

Source	R.A. (hours)	Dec. (deg.)	# In Bin	Expected Background	90% c.l. μ Flux Limit ($\mathrm{cm}^{-2}\mathrm{s}^{-1}\times10^{14}$)	90% c.l. ν Flux Limit ($\mathrm{cm}^{-2}\mathrm{s}^{-1}\times10^{4}$)	Assumed Distance (kpc)	90% c.l. ν Luminosity ($\mathrm{ergs\ s}^{-1}$)
LMC x-4	5.55	-66.38					50	
$\gamma = 2.3$			1	1.4	3.0	0.44		2.2×10^{41}
$\gamma = 3.0$			2	3.0	3.5	12		2.1×10^{42}
Cen. A	13.41	-42.93					5000	
$\gamma = 2.3$			1	0.3	3.7	0.54		1.8×10^{45}
$\gamma = 3.0$			1	0.6	3.5	12		2.3×10^{46}
Vela x-1	9.03	-40.48					1.4	
$\gamma = 2.3$			1	1.0	3.3	0.48		1.8×10^{38}
$\gamma = 3.0$			1	1.3	3.3	12		1.7×10^{39}
Crab	5.56	+22.01					2	
$\gamma = 2.3$			2	1.2	12	1.7		1.3×10^{39}
$\gamma = 3.0$			3	1.8	14	48		1.3×10^{40}
Her x-1	16.96	+35.36					5	
$\gamma = 2.3$			0	0.5	11	1.5		7.4×10^{39}
$\gamma = 3.0$			2	1.1	20	71		1.3×10^{41}
Cyg x-3	20.53	+40.91					12	
$\gamma = 2.3$			1	0.4	23	3.3		9.0×10^{40}
$\gamma = 3.0$			1	0.7	22	76		8.2×10^{41}
Geminga	6.51	+17.81					. . .	
$\gamma = 2.3$			1	1.1	7.8	1.1		. . .
$\gamma = 3.0$			2	1.7	9.8	34		. . .
SS433	19.18	+4.96					3	
$\gamma = 2.3$			1	0.9	6.2	0.90		1.5×10^{39}
$\gamma = 3.0$			1	1.5	5.9	21		1.3×10^{40}
3C273	12.47	+2.14					. . .	
$\gamma = 2.3$			0	1.1	4.1	0.60		. . .
$\gamma = 3.0$			0	1.9	4.1	14		. . .
Gal. Center	17.71	-28.90					10	
$\gamma = 2.3$			2	0.8	5.1	0.74		1.5×10^{40}
$\gamma = 3.0$			2	1.6	4.6	16		12.0×10^{40}

To this end, the coordinates of the objects LMC X-4, Cen A (NGC 5128), PSR 0531+21 (Crab), Her X-1, and Cyg X-3 were used as points from which computer-simulated neutrinos were generated and passed through the interaction and muon propagation Monte Carlo and data-reduction algorithms. Two separate neutrino source spectral indices γ were assumed, one for a high-energy spectrum ($\gamma = 2.3$) and one for a low-energy spectrum ($\gamma = 3.0$). The former value was chosen under the assumption that neutrino source spectra should be similar to that measured from such objects by X- and gamma-ray observations, while the latter value was selected because it is similar to that produced by cosmic-ray nucleons striking our own atmosphere. These specific sources were selected because: (1) they are likely *a priori* candidates for strong neutrino sources; and (2) their position in declination spans the aperture of the detector, allowing a calculation of the efficiency of recovering upward-going muon tracks as a function of source position.

The simulations showed that in order to enclose 90% of the muon events from a $\gamma = 2.3$ source, it is necessary to accept tracks within 7°0 from the source. For $\gamma = 3.0$ sources it is necessary to extend the cutoff to 9°5. Due to the poor absolute timing available during this detector run (i.e., the on-site computer clock), the cutoffs were extended to 8°5 and 11°0 respectively, to account for possible errors in the calculation of right ascension. Table 1 gives the number of events located within the angular cutoffs from the above-mentioned objects, plus a number of other celestial objects determined *a priori* to be possible sources of neutrinos.

Of course, in order to decide whether a given source candidate has a significant number of upward-going muon tracks near it, an estimate must be made of the number of background events expected from atmospheric neutrino interactions. This was done by drawing a number of "equivalent" cutoff circles at the same declination as the source candidate but offset in right ascension enough to preclude overlap. Assuming the distribution of detector live time to be flat in local sidereal time (a good assumption to within 7.5%), these equivalent circles should have the same acceptance aperture and collection efficiency as the circle around the actual source candidate. The expected background was then determined by simply totaling the number of events occurring inside the equivalent circles and dividing by the number of circles. Table 1 gives the results of this background determination for each source candidate. As can be seen, no source in the list has a significant excess of events arriving from its direction.

Using the Protheroe technique, 90% c.l. upper limits for the upward-going muon flux from each source are also given in Table 1, along with the corresponding neutrino flux and luminosity upper limits. These limits take into account the fraction of the live time the source was observable (i.e., below the horizon).

The limit on the upward-going muon flux from LMC X-4 of 3.0×10^{-14} cm^{-2} s^{-1} is less than the estimte of 5.0×10^{-14} cm^{-2} s^{-1} made by Cocconi (1985) based on an unpublished very high energy gamma-ray observation by the Adelaide air shower array at Buckland Park in 1985. Cocconi's estimate, however, is based on assumptions of neutrino flux enhancement relative to gamma-rays via attenuation at the source and by gamma-gamma interactions with the 3 K background radiation. Since the parameters for these mechanisms are extremely uncertain, the lack of a positive observation in neutrinos cannot be said as yet to seriously contradict the Adelaide result.

The limit on the upward-going muon flux from Cyg X-3 of 2.3×10^{-13} cm^{-2} s^{-1} is two orders of magnitude greater than the flux of 2×10^{-15} cm^{-2} s^{-1} predicted by Gaisser and Stanev (1985) based on a model of neutrino production by protons accelerated by a pulsar impinging on the atmosphere of a companion star. The poor limit is partially due to the fact that Cyg X-3 is only inside the detector's aperture for ~5 hr day^{-1}.

Through continued operation over the next few years, the IMB detector will be able to achieve flux sensitivity limits of possibly a factor of 2–3 better than those reported here. Still, if the Gaisser and Stanev calculation is correct for Cyg X-3, a significant improvement in sensitivity awaits the construction of a new generation of underground or undersea detectors.

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