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A SEARCH FOR ASTROPHYSICAL SOURCES OF LOW-ENERGY NEUTRINOS USING THE IMB DETECTOR

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ABSTRACT

The temporal structure of low-energy (20–60 MeV) neutrino interactions within the IMB-3 detector during 863 days of livetime between 1986 May and 1991 March has been analyzed. The neutrino data are consistent with expected cosmic-ray–induced neutrino interactions with no bursts evident (excluding SN 1987A). When combined with the 327 effective livedays of IMB-1 data, we place a 90% C.L. upper limit of ≤ 0.71 Galactic supernovae yr^{-1}. We have also performed a temporal correlation analysis with gamma-ray bursts (GRBs) using a subset of the low-energy neutrino data. No significant correlations were observed for coincidence windows of 1 minute, 1 hour, or 1 day.

Subject headings: ISM: cosmic rays — elementary particles — gamma rays: bursts — supernovae: general

1. INTRODUCTION

Neutrinos are thought to be produced in a number of astrophysical phenomena. These neutrinos, if detected, can probe fundamental processes occurring at the source. As experience has shown, (e.g., solar neutrinos and SN 1987A), there may be much to be gained by a study of low-energy neutrinos.

One category of astrophysical objects in which a study of low-energy neutrinos may be useful is gamma-ray bursts (GRBs). Determination of the sources capable of producing GRBs is one of the great mysteries of astrophysics. Whether through accretion processes, stellar collapse, or particle emission and decay, it is thought that neutrino and gamma-ray production may be related in many astrophysical processes. Therefore, it is reasonable to expect neutrino emission to be correlated with a GRB.

2. LOW-ENERGY NEUTRINO DATA

The low-energy neutrino data is a subset of the interactions contained within the volume of the Irvine-Michigan-Brookhaven (IMB) detector (Becker-Szendy et al. 1993). Specifically, it consists of 118 neutrino events firing between 40 and 70 photomultiplier tubes (PMTs) that were recorded over 863 livedays between 1986 May and 1991 March (the $\sim$50% duty cycle of IMB is due primarily to calibration periods and maintenance downtime). This range of PMTs corresponds to neutrino energies of $\sim$20–60 MeV. All eight neutrino events recorded from SN 1987A are in this range but are not included here. Analysis has shown that requiring events to have ≥ 40 PMTs significantly reduces the contamination from events which are due to cosmic-ray muon-induced spallation.

Since the products of low-energy neutrino interactions are not well correlated with the incident neutrino direction, evidence for neutrino emission from an astrophysical source comes from the observation of either burst structure in the neutrino data or from temporal correlations made with sources detected by other means.

The search for bursts of neutrinos is performed by counting, for each neutrino in the sample, the number of neutrinos falling within an arrival time window $\pm \Delta t$ around the chosen neutrino's detection time. Since the threshold of IMB was systematically lowered during its 6 year operation, the neutrino detection rate is not constant; therefore, the background is estimated using a Monte Carlo method which relies only on the recorded neutrino data sample and not on atmospheric neutrino production models. The Monte Carlo procedure randomizes each neutrino detection time within ± 10 days centered around the actual detection time (ensuring the new time is within the detector on-time). The constraint of ± 10 days is required in case the detector response is not uniform over a period greater than a few weeks. The expected background is the average over 10^3 trials of the number of n-fold coincidences occurring within the arrival time window around each neutrino time. Although consistent with Poisson statistics, this method more accurately reflects livetime and threshold effects.

Table 1 gives the number of n-fold coincidences between neutrinos in the data, along with the expected background $B_\nu(n)$, for three different temporal windows. Using the Monte Carlo procedure described above, the chance probability $P_{\geq \text{data}}$, of observing at least as many n-fold coincidences as is observed in the data is also given. The significance of the coincidence distribution was determined by comparing the total number of ≥ 1 fold concidences with the probability of observing at least that number in the 10^3 Monte Carlo trials. None of the coincidence distributions are statistically significant.

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TABLE 1

n-Fold ν/ν Coincidences

	$\Delta t = 1$ Minute			$\Delta t = 1$ Hour			$\Delta t = 1$ Day		
n	Data	$B_\nu(n)$	$P_{\geq \text{data}}$	Data	$B_\nu(n)$	$P_{\geq \text{data}}$	Data	$B_\nu(n)$	$P_{\geq \text{data}}$
0..........	118	117.96	0.964	118	116.56	0.236	98	93.23	0.182
1..........	0	0.04	...	0	1.43	...	18	21.53	0.816
2..........	0	0.00	...	0	0.01	...	2	2.93	0.787
3..........	0	0.00	...	0	0.00	...	0	0.28	...
4..........	0	0.00	...	0	0.00	...	0	0.03	...
≥5..........	0	0.00	...	0	0.00	...	0	0.00	...

Similar background estimates are obtained when the IMB-3 events are randomized ±100 days around the actual times or uniformly over the detector livetime because the IMB-3 event rate is close to being uniform for events with ≥40 PMTs.

Standard supernova theory, and our experience with SN 1987A (Bionta et al. 1987; Hirata et al. 1987), suggests that neutrino emission due to stellar collapse takes place on a timescale of many seconds. Thus, using the applicable 1 minute window we set a 90% C.L. upper limit on the rate of Galactic stellar collapse [including IMB-1 data (Dye et al. 1989)] of ≤ 0.71 SN yr^{-1}. The same limit is obtained by using the 1 hr coincidence window. Unlike the Galactic stellar collapse rate set by other neutrino detectors (e.g., Aglietta et al. 1992 give a limit of 0.45 SN yr^{-1}), IMB-3 is sensitive to supernovae with distances of ~100 kpc and can identify neutrino interactions on an event by event basis. This sensitivity is not only important in the search for Galactic supernovae, but crucial in the search for correlated neutrino emission from objects which are distributed throughout the Galactic plane and halo (possibly like GRBs).

3. GRB DATA

During the IMB-3 livetime the *GINGA* and *Solar Maximum Mission* (*SMM*) satellites were operational and recorded 53 GRBs (Dennis et al. 1988; Ogasaka et al. 1991). The energetics of mechanisms expected to have correlated neutrino and gamma-ray emission (pion production and decay, particle-antiparticle annihilation, etc.) suggest that the low-energy neutrino data is reasonable for comparison with the gamma-ray energies associated with most GRBs (< 100 MeV).

The search for coincidences between the detected neutrinos and GRBs is performed by counting the number of neutrinos arriving within a given temporal window around a GRB detection time. The appropriate window is model dependent. If GRBs are the result of stellar collapse-like events then neutrino emission is expected to take place on a timescale of order ≤1 minute. Since IMB recorded, on average, a cosmic-ray–induced neutrino in the energy range of interest every 12 calendar days, correlation times longer than a few days would not be detectable unless a neutrino burst is detected. Of course, some new exotic process may also produce GRBs. These arguments suggest a range of temporal windows: 1 minute, 1 hr, and 1 day.

The expected background due to random processes was determined using the same method described in § 2. The IMB-3 events used in this analysis are a subset (115 events) of the total neutrino data covering 788 livedays from 1986 May to 1990 October which coincides with operational periods of the satellites. The results of the ν/GRB correlation analysis are given in Table 2. None of the coincidence distributions is statistically significant (5% significance level).

The Monte Carlo method discussed above assumes that the background can be estimated based on the number of neutrinos observed in a window (i.e., ±10 days) around a GRB detection time. Actually the observed rate of neutrinos is a sample taken from a distribution (assumed Poisson) with an unknown mean. Thus, to confirm the results obtained with the Monte Carlo method, we apply a second method to the correlation analysis which includes the fact that the actual rate of accidentals is unknown.

A method has been developed (Alexandreas et al. 1993) which involves estimating the probability of Poisson fluctuations of both the observed number of source events and background events. Specifically, this involves calculating the probability of observing N_s events or more in the source bin (i.e., ±1 day around a GRB), given each possible fluctuation in the total number of background events, N_B. The result is a probability given by

$$P(\geq N_s, N_B, \alpha) = 1 - \sum_{n_s=0}^{N_s-1} \frac{\alpha^{n_s}}{(1+\alpha)^{N_B+n_s+1}} \frac{(N_B+n_s)!}{N_B!\,n_s!}, \quad (1)$$

where α is the ratio of the source bin size to background bin size. For the coincidence window of ±1 day and a background window of ±10 days, $\alpha = 0.1$; however, because of livetime effects the actual value of α may be different for a given GRB. The probability given above is computed for each GRB, and

TABLE 2

n-Fold ν/GRB Coincidences

	$\Delta t = 1$ Minute			$\Delta t = 1$ Hour			$\Delta t = 1$ Day		
n	Data	$B(n)$	$P_{\geq \text{data}}$	Data	$B(n)$	$P_{\geq \text{data}}$	Data	$B(n)$	$P_{\geq \text{data}}$
0..........	53	52.99	0.988	52	52.44	0.877	39	43.25	0.948
1..........	0	0.01	...	1	0.56	0.415	13	8.62	0.090
2..........	0	0.00	...	0	0.00	...	0	0.95	...
3..........	0	0.00	...	0	0.00	...	1	0.07	0.061
4..........	0	0.00	...	0	0.00	...	0	0.01	...
≥5..........	0	0.00	...	0	0.00	...	0	0.00	...

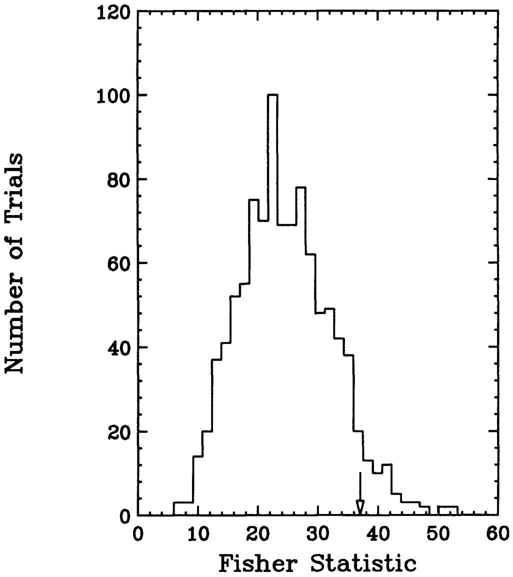

FIG. 1.—Fisher statistic distribution for 10^3 trials. The arrow indicates the value of the Fisher statistic obtained with the actual data. Roughly 6% of the trials exceed this value.

the distribution of 53 probabilities is compared to that expected from neutrino events distributed randomly in time. The value of N_s expected for each burst from randomly occurring events is estimated by choosing, for each GRB, a random deviate from a Poisson distribution whose mean is $\lambda = N_B \alpha$. The two probability distributions can then be compared using a statistical test developed by Fisher (Eadie et al. 1971). We define a parameter β as

$$\beta = -2 \log \prod_{i=1}^{53} \beta_i , \qquad (2)$$

where the β_i denote a probability for each GRB computed using equation (1). For a large number of events β is distributed as χ^2. Since in this case we have a small number of events we use the Monte Carlo method to determine the significance of the observed coincidences (letting the β_i be the probabilities defined in eq. [1]). Performing this calculation for 10^3 estimates of N_s (i.e., number of randomly occurring neutrino events) for each GRB, we find that the Fisher statistic distribution obtained with the actual data is not significant (~6% level), consistent with the result based on the Monte Carlo (see Fig. 1).

It should also be noted that no significant temporal correlations were seen with either the IMB-3 contained event sample (854 events, $E_\nu \leq 2.5$ GeV) (Becker-Szendy et al. 1992a) or the upward-going muon sample (430 events, $E_\nu \geq 2$GeV) (Becker-Szendy et al. 1992b) for the same time period, although there may be less expectation for correlated neutrino emission at these energies as discussed above.

4. DISCUSSION

Since the origin of GRBs is unknown, source distance and neutrino flux limits can be derived by scaling to the neutrino yield in IMB from SN 1987A. Thus for a given GRB source model, which also produces neutrinos, the following results can be used to determine a GRB distance lower limit. Based on the nonobservation of significant ν/GRB correlations, a model-dependent GRB distance lower limit can be derived at the 90% C.L. using

$$d^2 = \left(\frac{8\eta}{2.3}\right) d_0^2 , \qquad (3)$$

where $d_0 = 55$ kpc, the distance to SN 1987A. The factor of 8 is the neutrino yield in IMB from SN 1987A (discussed below). The parameter η is a scaling factor which represents the GRB source's neutrino luminosity and spectrum, as compared to that of SN 1987A, thus leading to a different neutrino yield in IMB. Thus the GRB distance lower limit is

$$d = 103\sqrt{\eta} \text{ kpc} . \qquad (4)$$

If the GRB dataset is assumed to be a homogeneous sample, then further limits can be set. As a working hypothesis we assume that all GRBs produce neutrinos with the same luminosity and spectrum as SN 1987A (e.g., Woosley 1992). Limits similar to those derived below can be found using any GRB model (not necessarily supernova-like), which produces neutrinos, by scaling to the neutrino yield in IMB of SN 1987A. The nonobservation of a single correlation of a neutrino interaction with any of the 53 GRBs then gives a 90% C.L. upper limit of 0.043 ν interactions per GRB. This limit can then be used to develop a lower bound on GRB distances by assuming a spatial distribution model for the sample, and then correcting for the different distances of the GRBs on a statistical basis. Using the previously derived neutrino emission limit, the mean inverse square distance is given by

$$\left\langle \frac{1}{d^2} \right\rangle = \left(\frac{0.043}{\rho \cdot d_0^2}\right) \qquad (5)$$

where the factor of ρ is the neutrino yield from SN 1987A and $d_0 = 55$ kpc. The relationship of the mean inverse square distance to the source distance depends on the spatial distribution of sources. It is not clear what the actual spatial distribution of GRBs is, but recent data suggests a spherical symmetry (Meegan et al. 1992). We consider two extremes: an infinitesimally thin spherical shell centered on the Galactic center and a volume distribution of cosmological origin. For distributions with a maximum radius r the mean inverse square distance is given by

$$\left\langle \frac{1}{d^2} \right\rangle = \frac{3}{r^2} \qquad (6)$$

for a volume distribution, and

$$\left\langle \frac{1}{d^2} \right\rangle = \frac{-1}{2Rr} \ln \frac{(1 - R/r)}{(1 + R/r)} \qquad (7)$$

for a shell distribution. The offset of the observer from the center of the shell is given by R ($R = 7.5$ kpc). The eight-neutrino events observed in coincidence with SN 1987A becomes 12 neutrino interactions within the volume of the IMB detector when corrected for triggering efficiency due to one-fourth of the detector being inoperative during the supernova. Without prior knowledge of a supernova, or detection of a burst of several events, the data reduction efficiency for finding the low-energy events used in this neutrino dataset is 70% based on comparisons between independent data analysis chains. Thus the neutrino yield is eight interactions for a supernova at a distance of 55 kpc. After 1988, modifications lowered the detector threshold thus increasing the neutrino yield per supernova; however, using the experimentally tested pre-1988 neutrino yield for the entire detector livetime gives the most conservative distance limit. Thus for stellar collapse-like GRBs $\langle 1/d^2 \rangle = 1.8 \times 10^{-6}$ kpc^{-2} which places a lower limit on the distance of 560 (1300) kpc for the shell (volume) distribution.

Particle and energy flux limits can also be obtained at the 90% C.L. Given that we observe no evidence of neutrino emission from GRBs (and assuming mono-energetic neutrino emission) a particle flux limit can be derived using

$$\phi \leq \frac{2.3m}{\sigma V \rho N_A N_p}, \tag{8}$$

where m is molar weight of water (18 g mole^{-1}), N_A is Avogadro's number, N_p is number of free protons in water (2), and ρ is density of water (1 g cm^{-3}). Here we use the total volume of the IMB detector ($V = 6.9 \times 10^9$ cm^3), and the dominant interaction in water, $\bar{\nu}_e + p \rightarrow n + e^+$, with cross section $\sigma = 7.2 \times 10^{-42}(E_\nu/10 \text{ MeV})^2$ cm^2. Thus the particle flux limit is $\phi \leq 6.9 \times 10^8(10 \text{ MeV}/E_\nu)^2 \nu$ cm^{-2} and the corresponding energy flux is $\phi_E \leq \phi E_\nu$ MeV cm^{-2}. If we assume the GRBs are a homogeneous sample then we can use the neutrino emission limit derived above (0.043ν per GRB) and set a particle flux limit of $\phi \leq 1.3 \times 10^7(10 \text{ MeV}/E_\nu)^2 \nu$ cm^{-2}.

5. CONCLUSION

The temporal structure of the IMB-3 low-energy neutrino dataset shows no evidence of bursts (excluding SN 1987A) with durations ≤ 1 day during 863 days of livetime between 1986 May and 1991 March. When combined with the IMB-1 dataset this leads to a 90% C.L. upper limit on the rate of Galactic stellar collapse of ≤ 0.71 SN yr^{-1}. Analysis also shows no evidence of temporal correlations with GRBs within a coincidence window of ≤ 1 day, thus allowing a distance lower limit to be set which rules out Galactic halo stellar collapse phenomena as the source of GRBs. Since neutrino and gamma-ray production may be related in many astrophysical processes, it is reasonable to expect neutrino emission from GRBs.

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