SEARCH FOR ASTROPHYSICAL NEUTRINO POINT SOURCES AT SUPER-KAMIOKANDE

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ABSTRACT

It has been hypothesized that large fluxes of neutrinos may be created in astrophysical “cosmic accelerators.” The primary background for a search for astrophysical neutrinos comes from atmospheric neutrinos, which do not exhibit the pointlike directional clustering that characterizes a distant astrophysical signal. We perform a search for neutrino point sources using the upward-going muon data from three phases of operation (SK-I, SK-II, and SK-III) spanning 2623 days of live time taken from 1996 April 1 to 2007 August 11. The search looks for signals from suspected galactic and extragalactic sources, transient sources, and uncataloged sources. While we find interesting signatures from two objects—RX J1713.7−3946
(97.5% CL) and GRB 991004D (95.3% CL)—these signatures lack compelling statistical significance given trial factors. We set limits on the flux and fluence of neutrino point sources above energies of 1.6 GeV.

Key words: galaxies: active – gamma rays: bursts – neutrinos – pulsars: general – supernova remnants

Online-only material: color figures

1. INTRODUCTION

The most plausible explanation of ultra-high-energy (UHE) cosmic rays is the so-called cosmic accelerator model, which posits that protons are accelerated by electromagnetic energy associated with objects with extended magnetic fields. It has been pointed out that cosmic accelerators, through pion production, are associated with objects with extended magnetic fields. It has been posited that protons are accelerated by electromagnetic energy as cosmic rays is the so-called cosmic accelerator model, which

\[ \gamma \propto E \]

\[ \Phi \propto E^{-\gamma} \]

Many models invoke the physics of shocks, which predicts a power-law spectrum that falls off like \( d\Phi / dE \propto E^{-\gamma} \) with a spectral index of \( \gamma \approx 2 \) (Learned & Mannheim 2000). The cross section for neutrino–nucleon scattering, however, depends roughly linearly on energy, and the effective detector volume increases with energy since high-energy muons can travel further in rock than low-energy ones. For the most likely range of spectral indices \( (\gamma = 2–3) \), the vast majority of astrophysical neutrino events at Super-Kamiokande fall into the category of upward-going muons described in Section 2. The spectrum of neutrino-induced muon events at Super-Kamiokande is shown in Figure 1.

2. UPWARD-GOING MUONS AT SUPER-KAMIOKANDE

Super-Kamiokande is a water Cherenkov detector located in Mt. Ikeno in central Japan under 2700 m water-equivalent rock overburden. The cylindrically shaped detector contains 50 ktons of ultrapurified water. It is divided by a steel structure into an inner detector (ID) equipped with 11,146 50 cm photomultiplier tubes (PMTs) aimed inward and an optically separated outer detector (OD) instrumented with 1885 20 cm PMTs aimed outward and equipped with wavelength-shifting plastic plates. The primary function of the OD is to identify charged particles that enter or exit the ID most of which are cosmic rays. Within the ID we define a 22.5 kton fiducial volume, within which detector response is expected to be uniform. Further details regarding the Super-Kamiokande detector design, operation, calibrations, and data reduction can be found in Fukuda et al. (2003) and Ashie et al. (2005).

Neutrino events with total deposited energy above \( \approx 100 \text{ MeV} \) are overwhelmingly due to atmospheric neutrinos from the decay of pions created by cosmic rays in the upper atmosphere. To a good approximation, the Earth is transparent to neutrinos up to energies of order 100 TeV. (The neutrino interactions observed by Super-Kamiokande represent a tiny fraction of the 1 GeV–100 TeV neutrinos passing through the Earth.)

Super-Kamiokande classifies events according to their energy and/or topology (see Figure 2). Fully contained (FC) neutrino events are those where interaction products are observed in the ID, with no significant correlated activity in the OD. Partially contained (PC) events are those where some interaction products exit the ID. Upward-going muon (upmu) events occur when a penetrating particle traveling in the upward direction enters and either stops in or passes through the detector. Upmu events are attributed to muons produced by neutrino interactions in the rock surrounding the detector. A cut on reconstructed path length ensures that upmu have energies greater than \( E_{\mu}^{\text{min}} = 1.6 \text{ GeV} \). FC, PC, and upmu events are associated with successively higher energy samples of neutrino interactions, ranging from 200 MeV for the lowest energy FC events to above 1 TeV for the highest energy upmu. We may thus think of each event type as a coarse energy bin so long as it is understood that the spectra for each event type overlap significantly.

Upmu are subdivided into stopping upmus, which stop inside the detector, and through-going, which pass straight through. The through-going upmu sample is further divided into showering and non-showering upmus with characteristic neutrino parent energies of 800 GeV and 100 GeV, respectively (Desai et al. 2007). For point sources with spectral indices near \( \gamma = 2 \), neutrinos are overwhelmingly likely to be observed in the through-going muon channel, and so we henceforth focus our attention on this data set. The upmu data set includes a small contribution (<1%) from nearly horizontal cosmic rays, which constitute an additional source of background for an astrophysical search. Other Super-Kamiokande astrophysical results making use of the upmu data include Desai et al. (2007), Fukuda et al. (2002), Thrane et al. (2009), Swanson et al. (2006), and Abe et al. (2006). We address nearly horizontal cosmic rays again in Section 3.

We utilize data from three stages of operation summarized in Table 1. The SK-II stage was characterized by diminished phototube coverage (about half the value for SK-I and SK-III). A comparison of solar-neutrino data from SK-I and SK-II has found no systematic differences in the two stages (Cravens et al. 2008). The reduced photocoverage during SK-II caused the upmu angular resolution to worsen marginally: 1°46 for SK-II in comparison with 1°05 for SK-III. (Angular resolution is defined such that 68% of the MC events have an angular separation between the true and reconstructed muon direction that is less than the resolution.) We take this difference into account in Section 6 in the construction of our search algorithm. SK-I and SK-III are similar in that they share the same number of PMTs, but they differ in that SK-III has additional reflective material called Tyvek® in the OD to optically separate the caps from the barrel to aid in event reconstruction.

3. LIKELIHOOD ALGORITHM

In this section, we develop a likelihood algorithm to maximize the discovery potential. We find it to be more sensitive by a factor of 2 than a previous search (Desai et al. 2007) wherein we counted the number of showering events in a 4° search cone (see also Abe et al. 2006). A similar algorithm has recently been presented as a means of searching for point sources with IceCube data (Braun et al. 2008).

To begin we construct an 8° search cone around the test direction, which is big enough to include over 99% of the point-spread function (PSF). We posit that any event, \( i \), falling in the search cone has a probability \( \alpha \) of being point-source signal, \( S \), and a probability \( (1 - \alpha) \) of being atmospheric background, \( B \),...
The likelihood function, the edge of the cone than at the center. Larger values of $\theta$ are more likely than smaller ones for the signal, when $\alpha$ = 1 the signal is maximal:

$$\langle \alpha \rangle = N_S/(N_S + N_B).$$

Here, $N_S$ and $N_B$ are respectively the number of events in the cone due to signal and background.

As it stands, the likelihood function depends only on the properties of each event (such as $\theta$) and not on the excess/deficit of events in the search cone in comparison to the expected number of events given $\alpha$, which we denote $N(\alpha)$, and which is

an additional measure of signal strength. $\bar{N}(\alpha)$ is the expected number of events given $\alpha$, whereas $N$ is the number of observed events.

To add this information to the likelihood function, we define a generalized likelihood function, denoted $L$, which is the product of $\mathcal{L}$ with a Poisson probability distribution on $\alpha$, as in Equation (4):

$$L(\alpha) = P_{\text{Poisson}} \mathcal{L}(\alpha) = e^{-\bar{N}(\alpha)} \frac{\bar{N}(\alpha)^N}{N!} \prod_{i=1}^{N} P(\alpha|\theta_i).$$

Noting that $\bar{N}(\alpha) = N_S + \bar{N}_B$, and recalling Equation (3), we see that $\mathcal{L}(\alpha) = \frac{\bar{N}_B}{1-\alpha}$. $\bar{N}_B$, the expected number of background events, can be determined by MC, and so we can eliminate all unknowns from Equation (4) in order to obtain Equation (5):

$$\mathcal{L}(\alpha) = e^{-\bar{N}_B/(1-\alpha)} \left( \frac{\bar{N}_B}{1-\alpha} \right)^N L(\alpha).$$

Having constructed the generalized likelihood function, we are now able to define a procedure for assessing signal strength. Given a search direction from which we can define $\theta_i$, we vary $\alpha$ in order to find the best-fit value, $\alpha_F$, which maximizes the generalized likelihood. Finally, we define a likelihood ratio, $\Lambda$, as in Equation (6), which serves as the ultimate indicator of signal strength:

$$\Lambda \equiv 2 \log [\mathcal{L}(\alpha_F)/\mathcal{L}(\alpha = 0)].$$

As $\Lambda$ gets larger, the probability of observing $\Lambda$ due to fluctuations in the atmospheric background, $P(> \Lambda)$, becomes smaller. $P(> \Lambda)$ is determined numerically using atmospheric MC.

4. SENSITIVITY

In one test described in Section 7, we measure $\Lambda$ at regularly spaced 0.5 intervals over the entire sky visible to Super-Kamiokande. First, we determine the largest signal at any point

**Figure 1.** Spectra of neutrino-induced upmus for a source with spectral indices $\gamma = 2$ (dashed) and $\gamma = 3$ (solid) and a minimum upmu energy of $E^\text{min}_\mu = 1.6$ GeV. The normalized spectra cross in the neighborhood of $\sim 200$ GeV.

**Table 1.** A Summary of the Data Set for this Analysis

| Phase   | Dates              | Events |
|---------|--------------------|--------|
| SK-I    | 1996 Apr 1–2001 Jul 19 | 1879   |
| SK-II   | 2003 Jan 17–2005 Oct 5 | 888    |
| SK-III  | 2006 Aug 4–2007 Aug 11 | 367    |

*Note. SK-III continued through 2008, but the data used here are limited to the dates indicated.*
in the sky, \( \Lambda_{\text{max}} \), and then we ascertain if it is large enough to constitute a statistically significant signal using the probability distribution, \( P(\Lambda_{\text{max}}) \), which is determined with MC. Studying \( P(\Lambda_{\text{max}}) \) (see Figure 3), we find that the detection of a source at decl. \( = -15^\circ \) (in the middle of the range of declinations visible by Super-Kamiokande) at 90% (99%) CL with an efficiency of 50% requires a signal of \( \Lambda_{\text{Max}} = 30.2 \) (34.7), respectively. We make a distinction between the false alarm rate, which determines the threshold for 90%/99% CL detection, and the number of events inside the cone was compared to the exposure time. (Both \( \alpha \) and \( \delta \) values of “showering” and “non-showering.” The atmospheric neutrino flux falls with a steep \( d\Phi_{\nu}/dE \propto E^{-3.7} \) spectrum in the relevant energy range, whereas point-source neutrinos are thought to fall off like \( d\Phi_{\nu}/dE \propto E^{-2} \). Since showering muons come from a higher energy parent neutrino population than non-showering muons, showering muons provide stronger evidence of point-source neutrinos than non-showering muons.

The likelihood function also depends on the search direction since they each vary with zenith angle, \( z \). We defer discussion of the neutrino flux calculation until Section 9.

6. LIKELIHOOD VARIABLES

Having introduced the formalism of the likelihood function, we are ready to give a full account of the variables on which it depends. In addition to angular separation, \( \theta \), the likelihood function depends on event type, denoted \( n \), which can take on values of “showering” and “non-showering.” The atmospheric neutrino flux falls with a steep \( d\Phi_{\nu}/dE \propto E^{-3.7} \) spectrum in the relevant energy range, whereas point-source neutrinos are thought to fall off like \( d\Phi_{\nu}/dE \propto E^{-2} \). Since showering muons come from a higher energy parent neutrino population than non-showering muons, showering muons provide stronger evidence of point-source neutrinos than non-showering muons.

The likelihood function also depends on \( n \) since the PSF is different for showering and non-showering events. (Showering events, which produce excess light through pair production, bremsstrahlung, and photonuclear effects, are on average slightly harder to reconstruct than non-showering events, which deposit energy primarily through ionization.) An example of the PSF for showering and non-showering muons is depicted in Figure 4.

The likelihood function also depends on detector geometry, denoted \( m \), which can take on values of “SK-I,” “SK-II,” or “SK-III.” The PSF and showering algorithm efficiency both vary with \( m \). The likelihood additionally depends on each event’s...
zenith angle, $z$, as well as the equatorial coordinates of the search direction: right ascension, R.A., and declination, decl. Dependence on $z$ arises from modest differences in the PSF at different zenith angles. (The fitter performs best for slightly upward-going muons and worst for straight upward-going muons due to detector geometry.)

Dependence on (R.A., decl.) enters through the number of expected background events in the cone, $N_B$. Atmospheric neutrinos have a well-studied zenith angle dependence due to the “secant theta effect” (Learned & Mannheim 2000) from mesons interacting in the atmosphere plus additional effects from oscillations and the detector shape. Each equatorial coordinate (R.A., decl.) is associated with a different locus of zenith angles and so the zenith angle distribution of atmospheric neutrinos manifests itself as a dependence on equatorial coordinates. Thus, each measurement of signal strength is characterized by the following variables:

$$\prod_i \{\theta_i, n_i|m_i, z_i, \text{R.A.}, \text{decl.}\}. \quad (9)$$

In order to determine the signal and background distributions we use MC. The background MC begins with atmospheric upmu vectors generated with NEUT (Hayato 2002) and using the Honda model of atmospheric neutrino flux (Honda et al. 1995). These upmu vectors become the input for a GEANT 3-based detector simulation. The same MC has been described in previous Super-Kamiokande publications, e.g., Ashie et al. (2005). The output of this simulation is then processed by the upmu reduction as if it were real data. We account for neutrino oscillations by applying a weighting factor proportional to the two-flavor survival probability, assuming maximal mixing and $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2$. The procedure for accounting for contamination from nearly horizontal cosmic rays using variations in the rock overburden is detailed elsewhere (see, e.g., Desai et al. 2007).

To generate signal MC, we first assume that the source is characterized by a $d\Phi/\nu dE \propto E^{-\gamma}$ power law with a spectral index of $\gamma = 2$. We obtain a spectrum for point-source upmus by multiplying $d\Phi/\nu dE$ by $P(E_{\nu}, E_{\nu}^{\text{min}})$—the probability that a neutrino with energy $E_{\nu}$ creates a muon with energy greater than $E_{\nu}^{\text{min}} = 1.6 \text{ GeV}$—and then integrating with respect to $E_{\nu}$ as in Equation (13). (We explore this equation in greater detail in Section 9 in the context of the neutrino flux calculation.) Each upmu vector is assigned a scattering angle according to its energy before it is fed into the detector simulation, which is followed by the upmu reduction.

7. FOUR SEARCHES

We conduct four searches for neutrino point sources. The first search, mentioned in Section 4, is the tabula rasa search. For this search, we make no assumptions about a priori suspected sources. We measure the signal strength $\Lambda$ at regular 0.5 intervals over the entire sky visible to Super-Kamiokande and record the largest observed value, $\Lambda_{\text{max}}$, which we compare with MC to determine if a statistically significant signal is present. This 0.5 spacing is chosen to be smaller than the width of the PSF (a little over a degree), but large enough to allow relatively fast computation. The second search is one for suspected candidates. In this search, we consider 16 objects identified in various publications as plausible bright sources of astrophysical neutrinos (Zhang et al. 2003; Guetta & Amato 2002; Huang & Pohl 2008; Aiello 2007; Link & Burgio 2005; Kistler & Beacon 2006; Bednarek et al. 2005; Gabici & Aharonian 2007). Candidates include magnetars (young pulsars with strong magnetic fields and periods on the order of seconds); plerions (aka pulsar wind nebulae, nebulae with an embedded pulsar); supernova remnants (SNRs; supernovae shockwaves colliding with surrounding gas); and microquasars (nearby black holes devouring a neighboring star). A summary of the candidates tested is provided in Table 2.

In the third search, we test for a correlation between upmus and 27 ultra-high-energy cosmic rays observed by the Auger experiment, which may be linked to active galactic nuclei (AGNs; Abraham et al. 2007; Hague 2009). We add the signal strength, $\Lambda$, from each direction to create a summed signal, $\Lambda_{\Sigma}$, the significance of which we evaluate with MC.

There are many ways to search for a correlation of neutrinos with AGNs, but this method has several advantages. There are more than 300 known AGNs within 75 Mpc of Earth. If we sum the signal from a great many cataloged AGN, we will effectively sample the entire sky, thereby diluting any signal. It is not clear how to pick the most neutrino-bright AGN, or how many to include in a summed signal analysis.

The 27 UHE events observed by Auger, however, constitute a conveniently small data set. Also, it is plausible that the brightest cosmic-ray objects are also the brightest in neutrinos. Since the Auger experiment is a southern hemisphere experiment looking at downward-going cosmic rays, and Super-Kamiokande is a northern hemisphere experiment looking at upward-going muons, all 27 UHE events in the Auger data set point to equatorial coordinates that are also visible to Super-Kamiokande. UHE cosmic rays are deflected by electromagnetic fields, but for a reasonable choice of parameters this deflection is small, $\sim 1^{\circ}$ (Lee et al. 1995). Finally, a test for a correlation of upmus with UHE cosmic rays is simple and transparent.

The fourth search is a search for upmus coincident with approximately 2200 gamma-ray bursts (GRBs) in the BATSE

| Source | Type | (R.A., decl.) | $\Phi^{90\%}$ (cm$^{-2}$s$^{-1}$) |
|--------|------|---------------|-------------------------------|
| GSR 1900+14 | Mag | (286.1, +0.3) | 1.12 $\pm$ 0.12 $\times 10^{-7}$ |
| GSR 0526−66 | Mag | (81.5, −66.0) | 1.15 $\pm$ 0.13 $\times 10^{-7}$ |
| 1E 1048.1−5937 | Mag | (162.5, −59.9) | 6.71 $\pm$ 0.74 $\times 10^{-5}$ |
| GSR 1806–20 | Mag | (272.2, −20.4) | 1.67 $\pm$ 0.18 $\times 10^{-7}$ |
| Crab | Pler | (83.6, +22.0) | 1.66 $\pm$ 0.18 $\times 10^{-7}$ |
| Vela X | Pler | (128.5, −45.8) | 6.87 $\pm$ 0.76 $\times 10^{-8}$ |
| G343.1-2.3 | Pler | (257.0, −44.3) | 6.81 $\pm$ 0.75 $\times 10^{-8}$ |
| MSH15-52 | Pler | (228.5, −59.1) | 1.12 $\pm$ 0.12 $\times 10^{-7}$ |
| RX J1717.7−3946 | SNR | (258.4, −39.8) | 2.67 $\pm$ 0.29 $\times 10^{-7}$ |
| Vela Jr. | SNR | (133.2, −46.3) | 9.16 $\pm$ 1.0 $\times 10^{-8}$ |
| MGRO J2019+37 | SNR | (305.2, +36.8) | 2.46 $\pm$ 0.27 $\times 10^{-7}$ |
| SS433 | MQ | (288.0, +5.0) | 1.16 $\pm$ 0.13 $\times 10^{-7}$ |
| GX339-4 | MQ | (255.7, −48.8) | 5.50 $\pm$ 0.61 $\times 10^{-8}$ |
| Cygnus X-3 | MQ | (308.1, +44.0) | 1.32 $\pm$ 0.15 $\times 10^{-7}$ |
| GRO J1655−40 | MQ | (253.5, −39.8) | 1.26 $\pm$ 0.14 $\times 10^{-7}$ |
| XTE J1118+480 | MQ | (169.5, +48.0) | 1.29 $\pm$ 0.14 $\times 10^{-7}$ |

Notes. The abbreviation “Mag” is for “magnetar,” “Pler” is for “plerion,” and “MQ” is for “microquasar.” Estimating the distance to these sources can be difficult and inexact as distance estimates often depend on measurements of what are assumed to be neighboring objects. The objects in this table are associated with estimated distances that range from 0.3 to 50 kpc.

Table 2 A List of 16 Candidates Considered to be Plausible Neutrino Point Sources with Associated Limits (at 90% CL) on $E_{\nu} > 1.6$ GeV Neutrino Flux
(Paciesas et al. 1999), HETE34, and Swift35 catalogs. Following a previously established procedure (Fukuda et al. 2002), we employ a ±1000 s window centered on the beginning of photonic observations of each GRB. This window size allows for any reasonable delay, positive or negative, between neutrino emission and photonic emission, while still providing a very small likelihood of random coincidences due to atmospheric neutrinos. Since the upmu rate at Super-Kamiokande is only about 1.6 day−1, the timing cut alone provides a powerful filter to remove atmospheric background. If there is a coincidence in time, we next determine if the event falls within the 8° search cone. If so, we evaluate the signal strength, Λ, of the coincident event. The probability that the event is due to atmospheric background is given by the product of the probability of a coincidence in time, with the probability of a coincidence in space, with the probability of measuring a signal strength ⩾ Λ:

\[ P_{BG} = P_{time} P_{space} P(\geq \Lambda). \] (10)

As always, we evaluate \( P(\geq \Lambda) \) with MC.

8. RESULTS

8.1. Tabula Rasa Search

The tabula rasa search yielded a signal of \( \Lambda_{\text{max}} = 19.1 \), which is well below the detection threshold. In fact, this signal is very small given the distribution of \( \Lambda_{\text{max}} \) in Figure 3, which prompted us to rerun the algorithm using “boot-strapped” values for local sidereal time. “Boot-strapping” in this context is the practice of assigning random values of local sidereal time to each event. This has the effect of scrambling the equatorial coordinates associated with each event while preserving other properties such as z and n. The second boot-strap run yielded \( \Lambda_{\text{max}} = 24.9 \), which, while still below the detection threshold, is more typical, giving us confidence that the small value of \( \Lambda_{\text{max}} = 19.1 \) is a reasonable fluctuation. Since no signal was observed, we set upper limits on the flux of point-source neutrinos.

Upper limits on the flux of point-source upmus/neutrinos as a function of declination are presented in Figures 5 and 6, respectively. The limits worsen at higher values of declination due to reduced exposure time. In Figure 7, we plot the neutrino flux limits obtained in this study (black) alongside an estimate of those obtained by AMANDA Abbasi et al. (2009a) for \( E_\nu > 1.9 \) TeV (approximated by the dotted red line), and limits by MACRO (Ambrosio et al. 2001) for \( E_\nu \gtrsim 1 \) GeV (approximated by the dashed blue). The dotted green line represents the approximate flux required to produce a signal at >90% CL with a 50% detection efficiency. (A color version of this figure is available in the online journal.)

respectively. The limits worsen at higher values of declination due to reduced exposure time. In Figure 7, we plot the neutrino flux limits obtained in this study (black) alongside an estimate of those obtained by AMANDA Abbasi et al. (2009a; red) and MACRO Ambrosio et al. (2001; dotted blue). Also included in this plot is the expected detection threshold for this study (dotted green) for the case of a 50% detection efficiency. We provide a sky map of the likelihood ratio Λ in Figure 8, in Figure 9 we provide a sky map of \( p(\Lambda) \) measured in sigma, and in Figure 10 we present the through-going muon data set in the form of a sky map.

8.2. Suspected Candidates

Of the 16 candidates listed in Table 2, we found a statistically interesting signature from one, the SNR RX J1713.7−3946, which yielded a signal of \( \Lambda = 8.5 \). Of the 26 events in the search

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34 http://space.mit.edu/HETE/Bursts/Data/
35 http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table
cone centered on SNR RX J1713.7–3946, approximately five are attributable to signal. RX J1713.7–3946 is one of the few known TeV shell-type SNRs. It is approximately 1 kpc away (Koyama et al. 1997; Fukui et al. 2003) and approximately 1600 years old (Wang et al. 1997). Using MC, we find the probability of an accidental signal of this magnitude to be 0.16%
8.3. Correlation with UHE Cosmic Rays

We found the summed signal from the directions of 27 UHE cosmic rays possibly linked to AGNs by the Auger experiment to be $\Lambda = 10.3$, which does not constitute a statistically significant signal. We therefore set a limit on the neutrino flux from each candidate (assuming a $\gamma = 2$ power law) are recorded in Table 2.

8.4. Correlation with Gamma-ray Bursts

Of the 2200 cataloged GRBs considered, 971 met the criteria of occurring during Super-Kamiokande live time with a zenith angle not greater than $8^\circ$ above the horizon. The data for this search do not include the recent so-called “naked-eye” GRB 080318B (Thrane et al. 2009), see also Abbasi et al. (2009).

Of the 971 GRBs visible to Super-Kamiokande, we observed one coincident GRB (designated 991004D) with the upmu data set. The upmu occurred $411$ s after the GRB and was separated by $3^\circ.4$. GRB 991004D was a long GRB with a duration of $T_{\text{90}} = 34$ s (Frontera et al. 2009). The total and peak gamma-ray fluence were not atypical nor was the spectral hardness. Key properties of the coincident GRB are listed in Table 3.

There were 3134 upmus considered in this data set with a live time of $2.3 \times 10^8$ s, which implies the mean time between upmu events is $\tau = 7.3 \times 10^4$ s. Thus, the Poisson probability for detecting one or more background events in the $t = 2000$ s window is given by

$$P_{\text{time}} = 1 - P(n = 0) = 1 - e^{-t/\tau} = 0.0270.$$  \hspace{1cm} (11)

The search used an $8^\circ$ half-angle search cone. Taking into account the fact that the search cone sometimes overlaps with the insensitive region ($z < 0$), the effective search cone angle is $6.7$. The approximate probability of a coincident background event falling inside the cone is given by

$$P_{\text{space}} = \frac{\Omega_{\text{cone}}}{\Omega_{\text{SK}}} = 0.043/11.37 = 0.00375.$$  \hspace{1cm} (12)

(Here, $\Omega_{\text{SK}}$ is the solid angle of the sky visible to Super-Kamiokande.) Thus, the probability of observing one or more background events within the $8^\circ$ cone is $P_{\text{coincidence}} = P_{\text{space}} P_{\text{time}} = 0.0038 \times 0.027 = 1.03 \times 10^{-4}$.

The signal strength for the coincident upmu was determined to be $\Lambda = 4.6$. From an MC sample of random background events (see Figure 12), we determine that the probability of observing $\Lambda \geq 4.6$ with background is $P_\Lambda = 0.486$.

It follows that the probability for observing a random coincidence with $\Lambda \geq 4.6$ in a single trial is $P_{\text{trial}} = P_\Lambda P_{\text{coincidence}} = 5.00 \times 10^{-5}$. The probability of observing no coincidence with $\Lambda \geq 8.5$ in one trial is, of course, $1 - P_{\text{trial}} = 0.99995$. If we test 971 GRBs, the probability of observing no coincidences with $\Lambda \geq 4.6$ in any of the 987 trials is given by $(0.99995)^{971} = 0.953$. Thus, the probability of observing one or more coincidences with $\Lambda \geq 4.6$ during 971 trials is $1 - 0.953 = 0.047$. Thus, testing 971 GRBs against the upmu data set, the single observed GRB—upmu coincidence has a $4.7\%$ probability of being due to random background. If we had used a smaller $\pm 500$ s window instead, the confidence level would improve from $95.3\%$ to $97.6\%$.

A previous study by Super-Kamiokande (Fukuda et al. 2002) found no evidence for a correlation of neutrinos with GRBs and set a $E_\nu > 1.6$ GeV fluence upper limit of $F_{\nu,90\%} > 0.038$ cm$^{-2}$. Using a $15^\circ$ search cone, Fukuda et al. (2002) reported a single coincidence—also GRB 991004D—but was unable to infer a
statistically significant signal. A likely reason for the apparent discrepancy in significance is that the algorithm presented here uses a smaller cone in concert with a likelihood function to filter out events that contribute to the expected background of the 15° cone search.

The best limits on GRB fluence currently come from the AMANDA experiment, which reports an upper limit of $1.4 \times 10^{-5}$ cm$^{-2}$ for neutrino energies between 250 and 10$^7$ GeV and assuming a spectral index of $\gamma = 2$ (Achterberg et al. 2008). In their search, AMANDA employs a timing window defined as the $T_{90}$ start and end times for the burst during which 90% of the total background-subtracted counts are observed. (The interval begins when 5% of the counts have been observed.) Typically, $T_{90}$ is on the order of seconds. While such a timing window is motivated by the plausible assumptions that GRB neutrinos are emitted at the same times as photons (and that their journey to Earth is unaltered by any new physics), it is nonetheless true that such a narrow window would not have allowed for detection of the 411 s delayed upmu observed in coincidence with GRB 991004D. The limits calculated by AMANDA, therefore, do not apply to models of GRBs (or new physics) that predict delayed or early neutrino arrival times.

Given AMANDA’s limits, along with the fact that there is little in the literature to suggest that GRB 991004D was in any way unusual, we interpret the observed signal as a background fluctuation and thereby obtain a limit on the average $E_{\nu} > 1.6$ GeV fluence of neutrinos from GRBs to be $F_{90\%} = 0.060 \pm 0.007$ cm$^{-2}$. This limit is slightly worse than the one obtained in the previous Super-Kamiokande study (Fukuda et al. 2002) due to the fact that a nearly significant discrepancy in significance is that the algorithm presented here is more sensitive, the apparent signal necessarily raises the upper limit. Since the new search algorithm employed here is more sensitive, the apparent signal from GRB 991004D is bigger, and so our limit actually worsens.

9. NEUTRINO FLUX LIMITS

In order to compute neutrino flux limits from muon flux limits, we follow (Thrane et al. 2009; Swanson et al. 2006; Desai et al. 2007) and assume a model for the source spectrum. It is typically assumed that $d\Phi_\nu / dE \propto E^{-\gamma}$ with $\gamma \approx 2$. Here we assume $\gamma = 2$ and investigate the implications of this assumption in Section 11. Given this assumption, the flux of neutrino-induced muons is peaked at high energies, between 1 GeV and 1 TeV depending on the spectral index (see Figure 1).

Upmu flux is related to the neutrino flux as in Equation (13):

$$\Phi_{\mu}(> E_{\mu}^{\text{min}}) = \int_{E_{\nu}^{\text{min}}}^{\infty} dE_{\nu} \frac{P(E_{\nu}, E_{\mu}^{\text{min}})}{P(E_{\nu}, E_{\nu}^{\text{min}})} S(z, E_{\nu}) \frac{d\Phi_{\nu}}{dE_{\nu}}. \quad (13)$$

Here, $\Phi_{\mu}(> E_{\mu}^{\text{min}})$ is the flux of upmus with energies above the minimum upmu energy of $E_{\mu}^{\text{min}} \equiv 1.6$ GeV. $P(E_{\nu}, E_{\mu}^{\text{min}})$ is the probability that a neutrino with energy $E_{\nu}$ creates a muon with energy greater than $E_{\mu}^{\text{min}}$ and $S(z, E_{\nu})$ is the Earth’s shadow factor. We use cross sections from the GRV94 parton distribution function (Glück et al. 1995) and the muon range is determined using Lipari & Stanev (1991) and M. Reno (2005, private communication):

$$P(E_{\nu}, E_{\mu}^{\text{min}}) = N_A \int_{0}^{E_{\nu}} dE_{\mu} \frac{d\sigma_{\text{CC}}}{dE_{\mu}}(E_{\mu}, E_{\nu}) R(E_{\nu}, E_{\mu}^{\text{min}}). \quad (14)$$

Here, $d\sigma_{\text{CC}} / dE_{\mu}(E_{\mu}, E_{\nu})$ is the charged current component of the neutrino–nucleon cross section (neutral current interactions do not produce muons). $R(E_{\mu}, E_{\mu}^{\text{min}})$, meanwhile, is the average range in rock for a muon with an initial energy of $E_{\mu}$ and a final energy greater than $E_{\mu}^{\text{min}}$:

$$S(z, E_{\nu}) = e^{-l_{\text{col}}(z) \sigma(E_{\nu}) N_A}. \quad (15)$$

Here, $l_{\text{col}}(z)$ is the Earth’s zenith angle-dependent column depth, and $N_A$ is Avogadro’s number scaled by the density of water. The column depth is calculated using the “Preliminary Earth Model” in Gandhi et al. (1996).

10. SYSTEMATIC ERROR

Two sources of systematic error are dominant in our calculation of the neutrino flux. One source is due to uncertainty in the neutrino–nucleon cross section (used in Equation (13)), which has an associated uncertainty of $\approx 10\%$ of upmu energies (Gandhi et al. 1996). To ascertain how this affects the neutrino flux uncertainty we calculate the flux by two ways, $\Phi_\nu \equiv \Phi(\sigma \rightarrow 110\% \sigma)$, $\Phi_\nu \equiv \Phi(\sigma \rightarrow 90\% \sigma)$, and estimate the uncertainty as half the difference.

Another systematic uncertainty arises from the fact that we only include charged current interactions in our calculation of the Earth shadow. While neutrinos interacting via charged current interactions produce muons and disappear from the incoming beam, neutrinos interacting via neutral current interactions can lose energy but remain in the beam. By including only charged current interactions in the Earth shadow, our calculation is too optimistic because neutral current interactions reduce the measured flux at the detector. If we include both charged and neutral current contributions, however, our calculation is too pessimistic since some neutrinos will reach the detector even after undergoing neutral current interactions.

Therefore, we calculate $\Phi$ by two ways: $\Phi_{\text{CC}} \equiv \Phi(\sigma = \sigma_{\text{CC}})$ and $\Phi_{\text{NC}} \equiv \Phi(\sigma = \sigma_{\text{CC}} + \sigma_{\text{NC}})$. The neutrino fluence is estimated as the average of $\Phi_{\text{CC}}$ and $\Phi_{\text{CC+NC}}$ and the uncertainty is estimated as half the difference. We add these two uncertainties in quadrature and find the total uncertainty in $\Phi_\nu$ to be $11\%$.

11. ASSUMPTIONS IN THE FLUX CALCULATION

Before concluding, we assess two assumptions made in the calculation of neutrino flux. First, we assume a spectral index of $\gamma = 2$, and so it is illuminating to address how the flux limits change if we chose a less favorable spectral index. Repeating the neutrino flux calculations with a more pessimistic spectral index of $\gamma = 3$, we find that the flux limits are raised by approximately 3 orders of magnitude due to the reduced neutrino–nucleon cross section at lower energies. We note that the two spectral indices yield comparable limits for the flux of $\sim 200$ GeV neutrinos where the normalized spectra interact (see Figure 1). Thus, numerical estimates of neutrino flux are extremely sensitive to assumptions about the source spectrum. While it is necessary to make an assumption about the nature of the source—and the $\gamma = 2$ power-law spectrum is certainly a useful standard assumption—it should be noted that until we know more about point-source spectra, numerical limits on neutrino flux are best suited for comparison between experiments.

A second assumption implicit in our flux calculations is that point sources emit neutrinos and not antineutrinos. The cross section for antineutrino–nucleon interactions is less than the cross section for neutrino–nucleon interactions due to the $V - A$ nature of the weak force, and this causes the limits for antineutrino flux to be $30\%$ higher than limits obtained for neutrinos.
12. CONCLUSIONS

We have constructed an algorithm for the purpose of detecting neutrino point sources. We find that this algorithm is more sensitive by a factor of 2 in comparison to a previous point-source search. Using the algorithm, we performed five tests. We set limits on $E_\nu > 1.6$ GeV neutrino flux at 90% CL as low as $6 \times 10^{-8}$ cm$^{-2}$s$^{-1}$ for declinations less than +54°. While not competitive with AMANDA’s limits, these limits are among the best for decl. < 0°. In a test of suspected sources, we looked for signals from 16 predetermined objects classified as potentially bright neutrino point sources. Of the 16 objects tested, we found one to have a high enough signal to warrant closer examination. The SNR, RX J1713.7−3946, was found to possess a signature at 97.5% CL taking into account trial factors. Northern hemisphere neutrino observatories such as ANTARES, NEMO, and NESTOR should be able to assess the possibility that the signal is real since the object is located at decl. = −39°.8.

Motivated by interest in correlations of AGNs with UHE cosmic rays, generated by recent Auger experiment results, we looked for a correlation of upms with UHE cosmic rays. We found no evidence for a correlation and set a limit on the average $E_\nu > 1.6$ GeV neutrino flux from Auger UHE event directions: $\Phi(90%) = (1.06 \pm 0.12) \times 10^{-7}$ cm$^{-2}$s$^{-1}$.

We performed a systematic search for correlations of upms with GRBs in the BATSE, HETE, and Swift catalogs. We found one coincidence (with GRB 991004D), which constitutes a signal of neutrino point sources with adequate confidence levels, some source candidates show signals that warrant future study.

The application of this algorithm to searches for astronomical point sources and many details of its design were motivated by discussions with Professor Thompson Burnett who helped develop a similar algorithm for use with the Fermi-GLAST Gamma-ray Space Telescope, and we gratefully acknowledge his input. Data on muon range and neutrino cross sections were graciously provided by M. Reno. The authors gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. Super-Kamiokande has been built and operated from funds provided by the Japanese Ministry of Education, Culture, Sports, Science and Technology as well as the U.S. Department of Energy and the U.S. National Science Foundation. Some participants have been supported by funds from the Korean Research Foundation (BK21) and the Korea Science and Engineering Foundation.

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