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High-Energy Neutrino Astronomy with the Super-Kamiokande Detector

A. Habig[a] for the Super-Kamiokande Collaboration
(a) Univ. of Minnesota Duluth Physics Dept., 10 University Dr., Duluth, MN 55812, USA
Presenter: A. Habig (ahabig@umn.edu), usa-habig-A-abs3-he23-poster

The Super-Kamiokande experiment has collected a large sample of high-energy neutrino events. These are primarily atmospheric neutrinos, but a bright enough astrophysical source could also be visible. The data have been examined for possible point and bursting neutrino sources, as well as possible WIMP annihilation signatures. No significant evidence for such sources have been found, and the resulting flux limits have been calculated.

1. Introduction

The highest energy neutrinos observed in the Super-Kamiokande experiment are seen via the upward-going muons which enter the detector when the neutrino interacts in the rock surrounding the experiment. Those muons which have enough energy to pass through the whole detector are called "through-going" and come from parent neutrinos with a typical energy of 100 GeV. Those which stop in the detector ("stopping") are made by neutrinos with typical energies of 10 GeV. More details of the data and their use in the analysis of neutrino oscillations can be found in [1]. An additional "showering" subset of the data with typical neutrino energy of 1 TeV has recently been identified by selecting upward-going muon events that experience radiative energy losses [2]. Also, an even higher energy sample has been recovered from extremely bright muons which saturate the Inner Detector and are bypassed entirely by the standard data reduction process.

The high energy end of the observed Super-K neutrino spectrum is of astronomical interest due to the steeply falling atmospheric neutrino spectrum. While neutrinos of energy greater than a GeV will produce leptons which follow the parent neutrino direction reasonably well, thus allowing one to identify where that neutrino came from on the sky, below a TeV the known atmospheric neutrino flux is much greater than predicted astrophysical neutrino fluxes [3]. The higher energy sample one can study, the better chance one has of picking out an astrophysical neutrino signal above the atmospheric neutrino background, and as a bonus the higher the parent neutrino energy the more closely the resulting muon follows the initial neutrino direction. Similar searches have been performed in the past. This paper presents new results from the same dataset as Super-K last presented [4]. A thorough explanation of some the general methods used was written by MACRO [5], and the AMANDA experiment is rapidly collecting a large dataset covering the northern sky [6].

2. Astrophysical Neutrino Searches with Super-K

The neutrino data come from the first (pre-implosion) phase of the Super-Kamiokande experiment, "SK-I", April 1996 through July 2001, a live-time of 1680 days. 1892 through-going (including 309 high-energy "showering" events) and 467 stopping muons were observed. Previous work [4] looked for any DC excesses indicating point sources, a correlation with the 1997 Mrk 501 outburst, and set DC flux limits around known high-energy sources. Super-K has also searched for neutrinos in coincidence with GRB's [7] and from WIMP annihilation's in astrophysical gravitational potential wells [8]. No sources have yet been found.

2.1 Soft Gamma Ray Repeaters

Soft Gamma Ray Repeaters ("SGRs") are a small class of bursting high energy sources. Unlike classic gamma ray bursts, they repeat, have a softer gamma spectrum, and are located in the galactic plane [9]. "Magnetar" models predict they might produce a neutrino flux, albeit a smaller one than to which Super-K is sensitive [10]. IPN data [11] was used to identify bursts from four known SGRs. Upward-going muons within 74 different windows of $\Delta T = \pm 1$ day and $\Delta\theta = 5^\circ$ around these bursts were selected, and one event was found. The background of random coincidences was found to be 0.013 events per window. With a trials factor of 74, the total expected background is 0.96 events, consistent with the one observed, so no evidence for neutrinos from SGRs was found [12].

2.2 Untriggered Burst Search

Extending the searches for GRBs, SGRs, and Mrk 501 outbursts to a more general case, an untriggered all-sky burst search was done. The aforementioned searches are examples of triggered burst searches – that is, the time and place of the astrophysical burst are used to look for correlations in the SK neutrino signal. To be free of trigger bias, most notably to have a chance of picking up neutrino bursts that for whatever reason were not seen by high energy electromagnetic telescopes, the data were examined for any self-correlation between upward-going neutrino-induced muons.

The method used was to regard each upward-going muon as a "trigger" itself, and to check for other such events arriving within an hour and 5^o on the sky. This is similar to the neutrino multiplicity analysis presented in [5, 4] with an additional time cut. One such doublet was found in the SK-I data. The expected background is 2×10^{-5} such coincidences, but when multiplied by the trials factors (number of upward-going muons minus one), the total chance of seeing such a chance coincidence is 5%, not statistically significant albeit tempting.

2.3 Searches with the Showering muon data subset

The higher neutrinos in the showering data sample offer a better chance to beat the soft background of atmospheric neutrinos. Thus, many of the same searches presented previously which used all upward-going muons have been re-done with just this high energy sample. These searches are: a search for DC excesses around known high-energy astrophysical objects; an all-sky search by checking for clustering of events in space; a search for an excess of events coming from the center of the Earth, Sun, and Galaxy to probe for WIMP annihilation; and a search for an excess of such events coming from the galactic plane, which probes for cosmic ray interactions in the interstellar medium. No statistically significant excesses were found. Fig. 1 shows the all-sky map of such events and the distribution of cluster multiplicities compared to the expected.

2.4 Diffuse Flux Limits with the Highest Energy Upward-going Muons [preliminary]

The very highest energy muons observed in Super-K are directed to a separate analysis chain, as nearly all the photomultiplier tubes ("PMTs") have been saturated, causing problems for the standard analysis tools. 52,214 events of more than 1.75×10^6 photoelectrons were observed in SK-I. As with more sedate muons, nearly all of these events are downward-going cosmic ray muons. Using the timing and charge of the Outer Detector veto shield PMTs, which collect less light and thus remain unsaturated, the directionality of these high-energy muons was checked. A result of one upward-going muon was found.

Detection efficiencies of muons with energies greater than 3 TeV were determined using Monte Carlo simula-

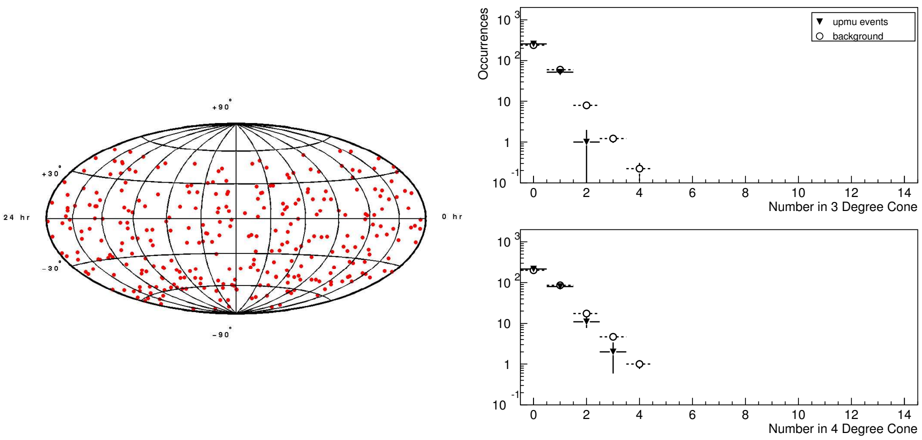

Figure 1. On the left is a map in Equatorial Coordinates of the high-energy "showering" subset of Super-K's upward-going muon data. These events show no evidence of unusual clustering which would indicate a possible point-source, as seen in the plots on the right. These graphs show the frequency of muon coincidences as a function of multiplicity, plotting the number of other events within 3° and 4° about each event. The triangles are the data, the circles from the atmospheric neutrino Monte Carlo and show the expected degree of coincidental clustering.

tions. Given the small number statistics involved, binning the data on the sky is not feasible, so the data was compared against a prediction for the whole sky given the known atmospheric neutrino spectrum. An expected background of 0.47 ± 0.25 atmospheric neutrino-induced extremely bright muons was found. Given the one observed event, an upper limit as a function of energy has been calculated for neutrino-induced muons of energies 3–100 TeV from possible astrophysical sources, to compare to similar searches from AMANDA [13]. These limits are shown in Fig. 2.

3. Conclusions

In an effort to identify possible astrophysical neutrinos, the SK-I dataset was examined in new ways to extract the highest energy neutrinos available to this detector. Showering muons exhibit radiative energy loss and come from a typical parent neutrino energy of 1 TeV. No statistically significant excess of these neutrinos was observed. The very highest energy muons in Super-K were recovered from the saturated PMT data. One was found to be upward-going, consistent with the expectations from the atmospheric neutrino spectrum. A search of all upward-going neutrinos compared to SGR outbursts also yielded no significant sign of an astrophysical source, as did an untriggered burst search checking for event clusters in time and space.

4. Acknowledgments

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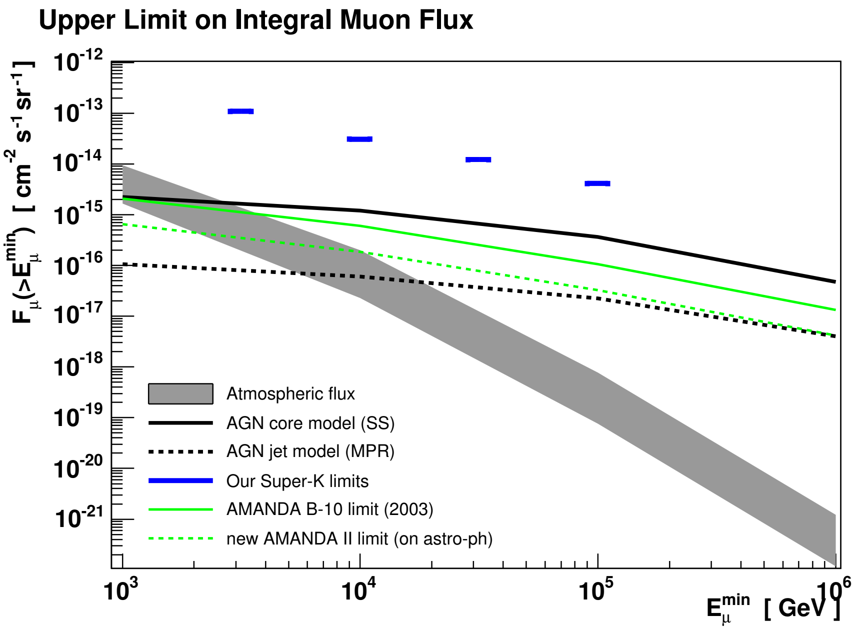

Figure 2. Given the observation of one upward-going muon which deposited more than 1.75×10^6 photoelectrons in Super-K compared to the expectation of 0.47 ± 0.25 events at these energies from atmospheric neutrinos, limits can be set on the muon flux induced by very high energy neutrinos coming from astrophysical sources. The preliminary upper limits from Super-K (blue dashes) are shown as muon flux above a threshold muon energy E_μ^{min}. These limits are compared to muon flux inferred from the AMANDA experiment's neutrino flux limits (green lines) [13], the expected muon flux due to atmospheric neutrinos (shaded region)and representative models of muon flux due to neutrinos from AGNs (black lines) [14, 15].

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