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A search for astronomical neutrino sources with the Super-Kamiokande detector

S. Matsuno, for the Super-Kamiokande collaboration

Dept. of Physics and Astronomy, University of Hawaii at Manoa

Abstract. High energy neutrino sources of astronomical origin are sought with data from the Super-Kamiokande detector. In this search, the upward going muons with a track length of greater than 7m are used. During first 4 years of operation, we have accumulated almost 1800 such muons, of which about 350 stopped in the detector and the rest are through going muons that exited the detector. This search, using the entire sample of upward going muon data in hand, revealed no statistically significant neutrino source, but set new limits on astronomical neutrino sources.

1 Introduction

Cosmic ray particles of extreme high energy exceeding 10^{20} eV have been observed in various air shower experiments (Hayashida, 1999). The energy spectrum of these cosmic rays shows no sign of cut off at that energy, even though there are many arguments suggesting otherwise. The exact mechanism of how these particles have been accelerated to that extreme high energy and where the acceleration took place still remain a mystery. High energy cosmic ray particles observed are predominantly charged nuclei, which readily interacts with both interstellar and intergalactic magnetic field. Hence, they have already lost information regarding their origin at the time they were observed on the earth.

Observations with neutral particles may reveal the source of these high energy cosmic rays. Observation with neutrinos is of great interest in this respect, along with that with high energy photons. Observations of γ-rays with energy around 1 TeV from various astronomical objects are reported and well established. However they seemed to be originated from electromagnetic process which are not suitable as a source of the observed extreme high energy cosmic ray particles. Also, high energy gamma-rays should interact with the cosmic background radiation and can not travel cosmological distances to reveal the source of cosmic rays. Because of the neutrino's very nature of low interaction cross section against both interstellar matter and radiation, it has an advantage compared to photons and neutrons.

Astronomical point source of high energy neutrino have been sought in various neutrino experiments and results published, including the recent work by the MACRO collaboration (Ambrosio, 2001). Although neutrinos from the Sun's nuclear reaction in its core, whose energy is up to around 10 MeV, have been observed by various experiments including Super-Kamiokande, no astronomical point source of neutrinos have been positively identified in the energy region around and above 1 GeV.

In this paper, we report a search for high energy neutrino point sources of astronomical origin using the first 4 years of Super-Kamiokande detector data.

2 Upward going muon

When muon neutrinos have undergone charged current interactions with rock surrounding the Super-Kamiokande detector, some of the resulting muons enter into the detector and are detected. In the downward going direction, the sheer number of atmospheric muons overwhelm these neutrino induced muons at the Super-Kamiokande depth. But, in the upward going direction, there is very little atmospheric muon contamination and neutrino induced muons can be detected reliably. There still is a tiny amount of contamination of atmospheric muons, mostly around the horizon, but this contamination is estimated to be less than 1% of neutrino induced muons. Also the contamination should be observed randomly in time, although they have prefered directions in the local coordinate of the Super-Kamiokande. Therefore, they do not concentrate in a certain direction of the sky. This allows us to search for astronomical neutrino sources using these upward going muons.

The use of upward going muons (UGM, hereafter) has an advantage in searching for astronomical neutrino point sources. This is because their parent neutrinos have rela-

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Correspondence to: S. Matsuno (shige@phys.hawaii.edu)

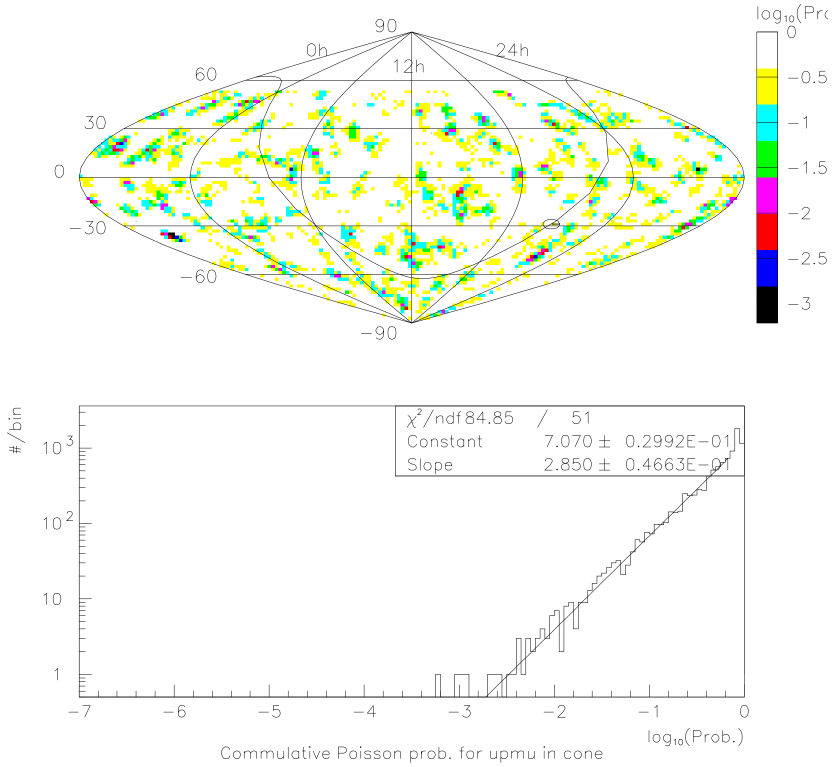

Fig. 1. Top panel: cumulative Poisson probability sky map in an equatorial coordinate. An S-shaped line in the figure shows the Galactic plane and an ellipse on it indicates the direction of the Galactic Center. Declination region above 54^o is not accessible with the Super-Kamiokande detector using UGM data.
Bottom panel: $\log_{10}$(probability) frequency distribution in the sky with a fit to an exponential function.

tively high energy compared to other neutrino events observed at Super-Kamiokande detector. Assuming the same energy spectrum as for the atmospheric neutrinos, the average energy of UGM's parent neutrinos ranges around 10 GeV for those stopping inside the detector and around 100 GeV for these going through the detector. In the case of the so called "contained events", whose interaction vertices and all the tracks are contained inside the detector, the parent neutrinos have an average energy of around 1 GeV. Higher energy neutrinos with their larger interaction cross-section and longer path length of the resulting muons will compensate their flux disadvantage especially for a harder spectrum expected for the neutrinos of astronomical origin compared to that of atmospheric origin.

An observed event is classified as an UGM, when all the following criteria have been satisfied. They are a) a muon event that has a clear entering signature into the detector, b) particle track's zenith angle cosine is less than or equal to 0, and c) length of the track inside the detector is greater than or equal to 7m. In case of through going UGM's, the track length is calculated as a geometrical distance between estimated entering and exiting points. In case of stopping muons, the effective energy loss inside the detector is used to calculate the track length.

In 1264 live observation days that span between April of 1996 when the Super-Kamiokande detector became operational and April of 2000, 345 stopping and 1416 through going UGM's have been observed. This accounts for an UGM flux of $2.1 \times 10^{-13}\ cm^{-2}s^{-1}sr^{-1}$ and consistent with atmospheric neutrino flux with neutrino oscillation of the mass difference of about $4 \times 10^{-3}eV^2$ and the mixing angle $cos^2(2\theta) \sim 1$ (Fukuda, 1999). The entire sample of 1761 UGM's is used in this analysis of searching for high energy neutrino sources of astronomical origin.

3 Poisson probability sky map

As the total observed UGM flux is consistent with that expected from atmospheric neutrinos with the oscillation, there should be very few events due to neutrinos from astronomical sources, if any. Due to the uneven exposure to each sky point (mostly declination dependence) and statistical fluctuation, just plotting the position of UGM's in sky indicates no useful information regarding from which direction statistically significant number of UGM arrive. To find the direction(s) on the sky from which the UGM events show statistically significant excess, a Poisson probability sky map is generated. In sky maps shown below, the bins are set in 2x2 degree around the equator. The right ascension interval is adjusted according to 1/cos(declination), so that each sky bin has a similar size in solid angle acceptance (igloo plot, see fig-1).

To generate a cumulative Poisson sky map, the number of UGM which are coming from within a 4 degree half angle cone drawn from the center of each sky bins are counted. Using background noise events expected in each bin, the cu-

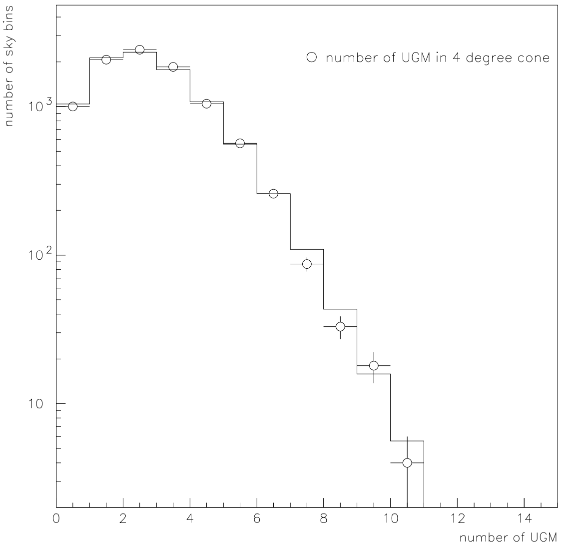

Fig. 2. UGM number distribution in the sky. The solid histogram in the figure shows expected distribution from noise obtained by "bootstrap method".

mulative Poisson probability, the probability of having the observed number of UGM's and above, for each sky bin can be calculated. The expected noise for each sky point is calculated using so called "bootstrap method". In this method, the real data is used to generate fake sky maps by swapping the event time and event direction randomly. In this analysis, 1000 fake sky maps having the same total number of UGM as the data are generated to obtain the average noise for each bin. Because of the usage of the real event time and direction, the systematics due to UGM angular distribution, detector angular acceptance, neutrino oscillation, live time unevenness in sidereal day, etc. should be all taken care of automatically in the noise estimate.

The resulting cumulative Poisson probability sky map is shown in Figure-1, along with the frequency distribution of $\log_{10}$(probability) fitted with a exponential function.

If there is a point source of neutrinos in our data, it should show up as an entry of having low $\log_{10}$(prob.) and the frequency distribution of $\log_{10}$(prob.) may become flatter. As shown in Figure-1, the lowest entry is in $\log_{10}$(prob) $\sim$ -3.2. Having $\sim 10^4$ sky bins in total and only one entry with a probability of $10^{-3.2}$ is completely insignificant. The fitted slope is a slightly steeper than expected value of 2.3, which is consistent with the case of no neutrino source. Therefore, no neutrino source was detected in this analysis.

4 UGM number distribution

Suppose a significant neutrino source exists in our data, it could show up as unusually high UGM count in some of sky bins compared to those expected from background noise. In the Figure-2, the UGM number in the cone distribution obtained above is shown with that expected from the noise to examine this possibility. This noise distribution is obtained using the "bootstrap method" mentioned above and shown as a histogram in the figure. The UGM number distribution is consistent with noise, especially in higher UGM count region. Hence no sign of an astronomical neutrino source can be found in this analysis either.

Potential Source Name	UGM observed in 4^o cone	noise expected	Accept. (cm^2)	Flux Limit $(cm^{-2}s^{-1})$
Cyg X-1	6	2.0	4.1×10^6	2.4×10^{-14}
Cyg X-3	1	1.8	3.5×10^6	1.0×10^{-14}
Her X-1	1	1.7	4.1×10^6	8.7×10^{-15}
Sco X-1	2	2.6	6.9×10^6	7.0×10^{-15}
Vela X-1	5	2.9	8.6×10^6	9.9×10^{-15}
Crab N.	0	1.8	5.1×10^6	4.1×10^{-15}
3C273	6	2.4	6.2×10^6	1.6×10^{-14}
Per A	1	1.9	3.4×10^6	1.1×10^{-14}
Vir A	1	1.7	5.7×10^6	6.3×10^{-15}
Coma cl.	2	1.7	4.7×10^6	1.0×10^{-14}
Gemminga	3	2.0	5.4×10^6	1.1×10^{-14}
Gal. C.	3	2.2	7.6×10^6	8.0×10^{-15}
Mrk 421	2	1.9	3.8×10^6	1.3×10^{-14}
Mrk 501	1	1.9	3.6×10^6	9.9×10^{-15}

Table 1. Up going muon flux limit for various potential neutrino sources in the sky.

5 Potential neutrino sources

Another method to search for statistically significant sources of neutrino in the sky is to test a few potential sources of neutrinos with UGM data. If there is a source that registers much more UGM's than expected from noise, it will be a neutrino source candidate. If not, UGM flux upper limit for these sources can be obtained. The sources tested here are compiled mainly among the high intensity X-ray sources plus some observed with high energy γ-ray experiments. The expected noise is calculated using the "bootstrap method" described above.

Table-1 shows the result of this analysis using the same 4 degree cone size around the source. As one can see from the table, the highest excess on observed UGM's above the expected noise was seen from Cyg X-1. We have observed 6 UGM's, where only 2 noise events were expected. This excess accounts for about 1.7% probable in terms of a cumulative Poisson probability. This is not statistically significant, because we have tried 14 sources and had to multiply the above mentioned probability by the trial factor of 14. Therefore, we have observed no statistically significant neutrino flux from the sources in this list and we can obtain only flux limits.

Using the number of UGM's observed, 90 % confidence

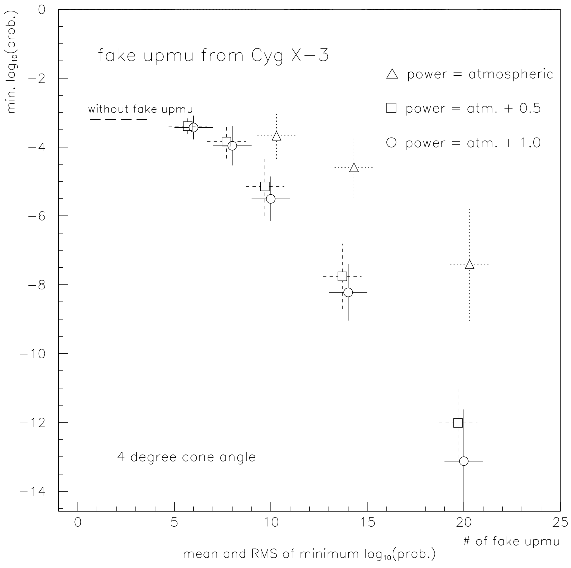

Fig. 3. minimum $\log_{10}$(probability) versus the number of fake upmu from a source added. Cyg X-3 is used as a test source in this figure.

level upper limit number of Poisson statistics can be obtained. This number is used to calculate flux limit for the source by deviding by the detector acceptance for the source direction and the observing live time. Table-1 also shows the results of flux limit calculation for the selected potential neutrino sources.

6 MC simulation

To investigate the number of UGM's required for a neutrino source in the sky to be detected, Monte Carlo based neutrino events from a trial source direction were generated. These fake events are mixed with the real data and analyzed to see how low the cumulative Poisson probability of the point can become.

In Figure-3, average and RMS of minimum $\log_{10}$(prob.) are plotted against the number of fake UGM from an injected source added. In this figure, Cyg X-3 has been chosen as a sample source. The different marks in the figure show the results with different exponents of a power function on the neutrino energy spectrum tested, namely -1.7, -2.2, and -2.7.

For the case of -1.7 and -2.2 exponent, the result above number of UGM being 8 fits well to a straight line. If we took intersect of this fitted line and $\log_{10}$(prob.)=-3.2, which is the minimum $\log_{10}$(prob.) value with no additional UGM from the source, as a measure of the number necessary for a source to be detected, this result shows it to be 7.0 ± 0.7 and 6.8 ± 0.5 for the case of -1.7 and -2.2 exponents respectively. With the current exposure of the Super-Kamiokande detector against Cyg X-3, 7 UGM's correspond to a UGM flux of 1.85 $\times\ 10^{-14}$ cm^{-2} s^{-1}.

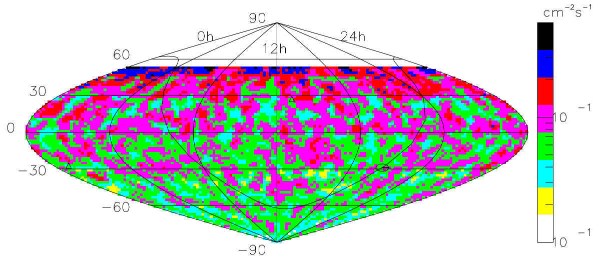

Fig. 4. 90 % C.L. flux limit sky map in the equatorial coordinate. Flux shown in this figure is in unit of $cm^{-2}s^{-1}$. As noted in Fig-1, declination above 54^o is not accessible with UGM.

7 flux limit sky map

As no neutrino source has been found in our data as described above, we can obtain flux limits for the entire sky that the Super-Kamiokande detector can monitor using UGM. The same method as for calculating the flux limit from potential sources is employed to obtain the 90% (Poisson c.l.) flux limit for the each sky point. The resulting sky map is shown in Figure-4. The limit is more stringent at southern sky, which reflects longer exposure to that region with UGM data.

8 conclusion

Various methods of detecting a statistically significant excess were employed on the Super-Kamiokande UGM data to search for astronomical neutrino point sources. None showed statistically significant excess and the flux upper limit for the various potential neutrino sources is obtained, many of which exceed existing limits obtained from other experiments.

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