A Search For Astronomical Neutrino Sources With The Super-Kamiokande Detector

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Abstract

Upward-going muons logged by the Super-Kamiokande detector during the SK-I running period (1996-2001), are used in a search for astrophysical point sources of neutrinos. The results of two independent analyses of all-sky surveys are presented. The data are also examined for an excess of muons associated with the extended flaring episode of Markarian 501 in 1997. No significant evidence for astrophysical point sources of neutrinos is found. Confidence limits on the maximum observationally consistent neutrino flux that might be coming from selected source candidates are presented.

1. Introduction

The neutrino's low interaction cross section with both interstellar matter and radiation gives it a huge advantage compared to photons and cosmic rays as a carrier of information at the highest energies. High energy neutrino point sources have been sought in various experiments [1]-[4] but no such source has been positively identified in the energy region above 1 GeV. Because of the high background from atmospheric muons in the downward direction, neutrino sources are sought using upward-going muons (UGM). The energy spectrum of astrophysical neutrinos is presumed to be harder than that of atmospheric neutrinos, making the ratio of astrophysical to atmospheric neutrinos greater at higher energies.

Super-Kamiokande (SK), a 50 kton water Cherenkov detector, is described elsewhere [5]. In 1679.6 live observation days that span between April 1996 and July 2001, 486 stopping and 1901 through-going UGMs were observed. The average UGM flux of $2.1\times10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ is consistent with the expected atmospheric neutrino flux [6]. The entire sample of 2387 UGMs is used in these analyses to search for high energy neutrino sources of astronomical origin.

2. Analysis Methods

Two separate groups within the SK collaboration performed independent analyses on the UGM data set. Both generated Poisson probability sky maps and

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derived flux limits for selected source candidates and one analysis included a time correlation study of MRK 501 and two-point correlation study [7].

To generate a cumulative Poisson sky map, the portion of the sky visible to UGMs (below 53.58° declination) was divided into bins. One search used $8^\circ \times 8^\circ$ bins; the other used $2^\circ \times 2^\circ$. The Poisson probability is calculated using the mean background expected in each bin. Both analyses calculated the expected "noise" using the "bootstrap" method [8]. Because real event times and directions are used to generate background, the systematics due to the angular distribution, detector angular acceptance, neutrino oscillation, live time unevenness, etc. are included in the noise estimate. Both analyses yielded similar Poisson probability sky maps (figure-1), along with a frequency distribution of $\log_{10}$(probability) fitted to a power law function. A point source should show up as an anomalous entry far to the left of the main distribution. However, data consistent with the background would yield no anomalous bins, which is what is seen here.

Since the energy spectrum of neutrinos from astronomical sources is thought to be harder than that of atmospheric ones, it is worthwhile to test a partial UGM sample whose parent neutrino's mean energy is higher than that of all UGMs. Through-going UGMs are a good subset since the average energy of their parent neutrinos is about 100 GeV, compared to 10 GeV for stopping UGMs. However, an analysis using only through-going UGMs did not yield significantly different results from the analyses that used the entire sample.

Both analyses looked at selected source candidates. The candidate list included known sources of high intensity X-rays and matched lists used by similar experiments. Upper limits on UGM flux were derived (figure-2). One analysis used 4°-halfwidth cones around the source candidates to compute the flux limit and the other used 6°-halfwidth cones to be sure all events associated with the source were counted. Monte Carlo studies showed that the angle between parent neutrino and the reconstructed muon track has a standard deviation of $\sim 4^\circ$.

One analysis included a two-point correlation function study. Because this study and the time correlation with MRK 501 were performed before July 2001, only 1479.6 livetime days of the total 1679.6 were used [7]. The two-point correlation function is described elsewhere [9]. It involves drawing concentric circles around every data point, counting the pairs of points that are separated by a certain angle, $n(\theta)$, and comparing this with the number expected, $m(\theta)$. The two-point correlation function, $w(\theta)$, is defined as

$$n(\theta) = m(\theta)[1 + w(\theta)]. \tag{1}$$

No significant clustering would yield $w(\theta) \sim 0$ for all θ as is seen (figure-3).

The 1997 flaring episode of Markarian 501 between Feb. and Oct. of 1997 offered an attractive opportunity to do a time coincidence study. A 6°-halfwidth cone centered on MRK 501 was used to count events during and near times of heightened activity, which accounted for 13.47% of the detector live time. Of the remaining 86.53%, 67.52% was logged definitely before or after the flaring event. The total on-source live time, 13.47%, could be called background plus signal and 67.52% could be called background only. Ten off-source cones chosen in the same declination band plus 0.6752 of the on-source cone were used to estimate the background. So the exposure ratio of background plus signal to background only is 0.1347/10.6752 = 0.01262. In the data, 182 background-only events were counted. Multiplying by the exposure ratio, a null hypothesis would suggest that background alone should produce ∼2.30 on-source events during flare periods. Two events were actually observed and at least 9 events would be required for a 3σ detection, so this test did not produce any evidence for MRK 501 as a point source. Time correlations with the BATSE γ-ray burst data were also studied but yielded no positive detections.

In addition to Poisson probability sky map and select source candidate methods, a third analysis team used the clustering method, also used by MACRO [3]. This method involves counting the number of events in a cone drawn around each event. Using cones of half-widths 1.5°, 3°, and 5° and using Monte Carlo events as added background, no statistically significant sources were found.

3. Conclusion

Various methods of searching for a statistically significant excess of UGMs in the sky have been employed on the SK data in two different analyses to look for astronomical neutrino sources. None of these methods have shown an excess that would suggest the existence of a point source of high energy neutrinos. Upper limits for the flux of various potential neutrino sources are obtained, many of which improve existing limits obtained from other experiments. A flux-limit sky map of the SK UGM data has also been obtained, which sets a limit of about $10^{-14}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ or better for most of the sky bins.

4. References

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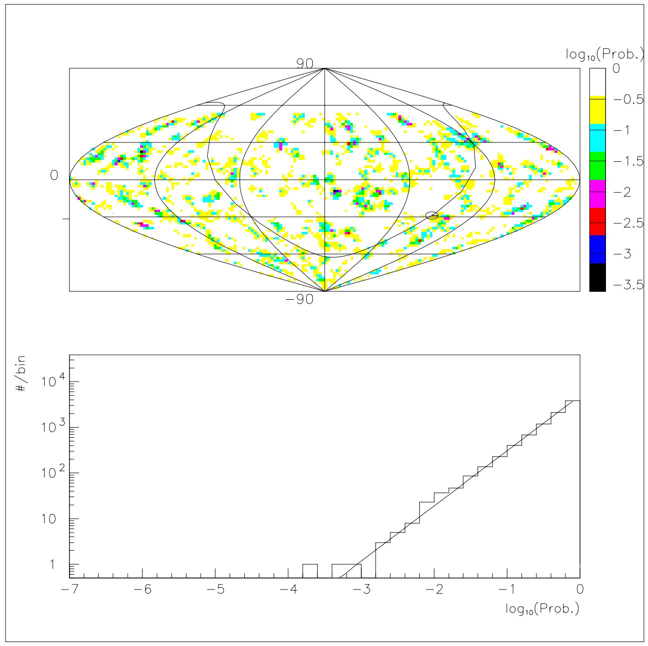

Fig. 1. Top panel: Cumulative Poisson probability sky map in equatorial coordinates. The S-shaped line shows the galactic plane and the ellipse on it marks the galactic center. Bottom panel: The $\log_{10}$(probability) frequency distribution in the sky, fit to a power law.

Potential Source	4° cone Limit	6° cone Limit	Prev Limit
Cyg X-3	1.3	4.2	6.6
Her X-1	0.90	0.77	3.3
Sco X-1	0.66	0.49	0.85
Vela X-1	0.84	1.3	0.26
Crab Neb	0.52	1.3	2.5
3C273	1.0	1.7	-
Geminga	0.85	0.94	1.1
Gal Cen	0.35	0.73	0.34
MRK 421	0.97	0.83	5.0

Fig. 2. UGM flux limits for potential sources in units of $10^{-14} cm^{-2} s^{-1}$. The last column shows limits from MACRO [3]

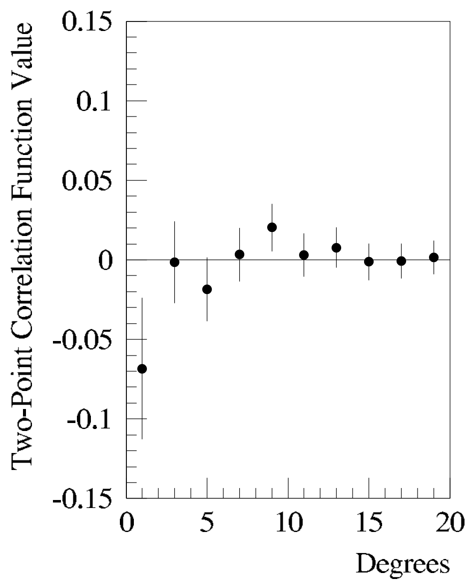

Fig. 3. The angular two-point correlation function, at small angles, tabulated in two degree increments. Error bars are due to counting of $n(\theta)$ and uncertainty in $m(\theta)$.