IceCube Time-Dependent Point Source Analysis Using Multiwavelength Information

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***Abstract*. In order to enhance the IceCube's sensitivity to astrophysical objects, we have developed a dedicated search for neutrinos in coincidence with flares detected in various photon wavebands from blazars and high-energy binary systems. The analysis is based on a maximum likelihood method including the reconstructed position, the estimated energy and arrival time of IceCube events. After a short summary of the phenomenological arguments motivating this approach, we present results from data collected with 22 IceCube strings in 2007-2008. First results for the 40-string IceCube configuration during 2008-2009 will be presented at the conference. We also report on plans to use long light curves and extract from them a time variable probability density function.**

***Keywords*: Neutrino astronomy, Multiwavelength astronomy**

I. INTRODUCTION

IceCube is a high-energy neutrino observatory currently under construction at the geographic South Pole. The full detector will be composed of 86 strings of 60 Digital Optical Modules (DOMs) each, deployed between 1500 and 2500m below the glacier surface. A six string Deep Core with higher quantum efficiency photomultipliers and closer DOM spacing in the lower detector will enhance sensitivity to low energy neutrinos. Muons passing through the detector emit Čerenkov light allowing reconstruction with $\lesssim 1°$ angular resolution in the full detector and about $1.5°$ (median) in the 22 string configuration. In this paper we describe the introduction of a time dependent term to the standard search for steady emission of neutrinos presented in Ref. [3]. We apply it in a search for periodic emission of neutrinos from seven high-energy binary systems and for a neutrino emission coincident with a catalogue of flares occurring when IceCube was taking data in its 22 string configuration. We also describe an extension of the method that uses multi-wavelength (MWL) lightcurves to characterize neutrino emission.

II. TIME DEPENDENT POINT SOURCE SEARCH

An unbinned maximum likelihood ratio method, using a test statistic that compares a signal plus background hypothesis to a background-only one, has been used for the search for point sources of neutrinos in IceCube [1]. We use the angular and energy distribution of events as information to characterize the signal with respect to the background. In the analysis of the 22-string data we use the number of hit DOMs in an event as an energy estimator, while for the 40-string configuration we use a more sophisticated energy estimator based on the photon density along the muon track. The analysis method returns a best-fit number of signal events and spectral index (though with a large error that depends on the number of events near the celestial coordinate being tested).

We use the IceCube 22-string upward-going neutrino event data sample of 5114 events collected in 275 days of livetime between May 31, 2007 and April 5, 2008 (which includes misreconstructed atmospheric muon contamination of about 5%). Selection cuts are based on the quality of the reconstruction, on the angular uncertainty of the track reconstruction ($\sigma < 3°$) and on other variables such as the number of DOMs hit by the direct Čerenkov light produced by muons. Fig 1 shows that the time distribution of these atmospheric neutrino events is consistent with a flat distribution.

Neutrinos from a point source are expected to cluster around the direction of the source and to have a spectrum $\frac{dN}{dE} \propto E^{\gamma}$ with spectral index $\gamma \sim -2$ as predicted by 1^{st} order Fermi acceleration mechanisms. On the other hand, the background of atmospheric neutrinos is distributed uniformly in right ascension and has an energy spectrum with $\gamma \sim -3.6$ above 100 GeV. We construct a signal probability distribution function (pdf):

$$S_i = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}} * E(E_i|\gamma) * T_i, \qquad (1)$$

where σ_i is the reconstructed angular error of the event [2], $\vec{x}_i - \vec{x}_s$ the angular separation between the reconstructed event and the source, E is the energy pdf with spectral index γ, and T_i is the time pdf of the event. The background pdf is given by:

$$B_i = B(\vec{x}_i) * E_{bkg}(E_i) * \frac{1}{L} \qquad (2)$$

where $B(\vec{x}_i)$ is the background event density (a function of the declination of the event), E_{bkg} the energy

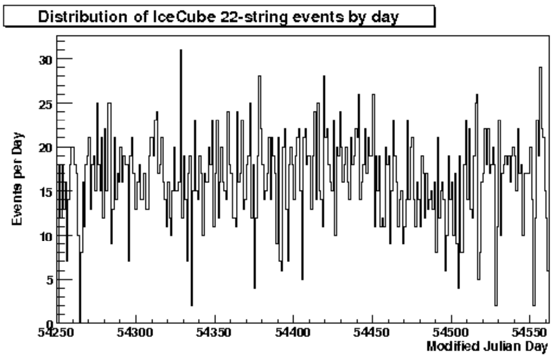

Fig. 1. Time distribution of the 22-string neutrino events.

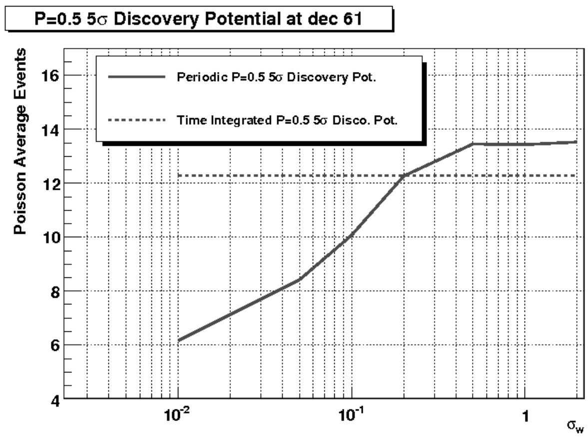

Fig. 2. Comparison of discovery potential at 5σ and 50% probability between the time-integrated and time-dependent methods for LSI +61 303.

distribution of the background, and L the livetime. The background pdf is determined using the data, and the final p-values for these analyses are obtained by comparing scrambled equivalent experiments to data. Scrambled times are drawn from the distribution of measured atmospheric muon event times, taking one event per minute to obtain a constant rate.

The analysis method gives more weight to events which are clustered in space and at energies higher than expected from the atmospheric background. In this work we present the results which include for the first time a time dependent term in the pdf. Results are given in terms of p-values, or the fraction of the scrambled samples with a higher test statistic than found for the data.

III. Binary System Periodicity Search

One class of high-energy binary systems, microquasars, includes a compact object with an accretion disk emitting relativistic jets of matter. Jets are assumed to accelerate protons, hence pp and $p\gamma$ interactions are possible. The two microquasars LS 5039 (which is out of the IceCube field of view) and LSI 61 +303 [4] have been observed to emit TeV gamma-rays modulated with the orbital phase of the systems. H.E.S.S. detects the minimum of the photon emission for LS 5039 during the superior conjunction, where the compact object is behind the massive star [5]. The gamma ray modulation can be interpreted as an indication of absorption of gammas emitted from the compact object. Nonetheless, the modulation could be very different in neutrinos, where neutrino production depends on how much matter is crossed by the proton beam on which interactions and decays depend. Since we assume that the modulation is related to the relative position of the accelerator with respect to the observer, we also include in our search objects for which no TeV modulation has yet been observed, using the period obtained from spectroscopic observations of the visible binary partner. We then leave the phase as a free parameter to be fit. Due to low statistics, a Gaussian will be adequate to describe the time modulation. Hence our time-dependent pdf is:

$$T_i = \frac{1}{\sqrt{2\pi}\sigma_w} e^{-\frac{|\phi_i - \phi_0|^2}{2\sigma_w^2}}, \qquad (3)$$

where σ_w is the width of the Gaussian in the period, ϕ_i is the phase of the event and ϕ_0 is the phase of peak emission. The phase takes a value between 0 to 1.

We find that this time-dependent method has a better discovery potential than the time-integrated analysis if the sigma of the emission is less than about 20% of the total period (Fig. 2). Since there are more degrees of freedom, the time-dependent analysis will perform worse if neutrinos are emitted over a large fraction of the period.

We examined seven binary systems, listed in Tab. I, covering a range of declinations and periods. There was no evidence of periodicity seen for any of the sources tested. The most significant result for this search has a pre-trial p-value of 6%, we expect to see this level of significance from one of our seven trials in 35% of scrambled samples, hence we find no evidence for periodicity.

Object	RA (deg)	Dec (deg)	Period (d)	p-value
LSI +61 303	40.1	+61.2	26.5	0.51
Cygnus X-1	299.6	+35.2	5.6	0.63
Cygnus X-3	308.1	+40.9	0.2	0.09
XTE J1118+480	169.5	+48.0	0.2	0.11
GRS1915	288.8	+10.9	30.8	0.61
SS 433	287.9	+5.0	13.1	0.06
GRO 0422+32	65.4	+32.9	0.2	0.39

TABLE I
System name, equatorial coordinates, period and pre-trial p-value.

IV. Multiwavelength Flares Analysis

In high-energy environments, $p\gamma$ and pp interactions produce pions and kaons that decay into photons and neutrinos. Thus, we expect a correlation between TeV γ and ν_μ fluxes. Blazars and binary systems exhibit variability, with flares often observed to correlate in several photon wavebands. Hence, if TeV information is not available, we can use X-ray and optical data as well. We use this expected time correlation between photons and neutrinos to suppress the background of atmospheric neutrinos, which have a random distribution in time, by looking for neutrino emission in time windows selected based on MWL information. By restricting our search we need fewer events to achieve a 5σ signal than with the time-integrated search.

We use MWL observations to create a catalogue of flares from blazars and binary systems which have states of heightened non-thermal emission. We determine the time window of our search based on the MWL data to characterize the time and duration of peak brightness.

A. Selection of Flares

To collect a list of interesting flares we monitored alerts such as Astronomer's Telegram or GCN for sources observed undergoing a change of state which may produce heightened neutrino emission. The selected catalogue is presented in Tab. II and illustrated here:

- **3C 454.3** flares were measured by AGILE GRID during July 24-30, 2007 [8] and again during Nov. 12-22, 2007 [9].
- **1ES 1959+650** was seen by INTEGRAL in a hard flux state (Nov. 25-28 2007 [6]). Later Whipple obtained a few measurements around December 2-7 [7] which we also selected for investigation.
- **Cygnus X-1** had a ”giant outburst” seen by Konus-Wind and Suzaku-WAM [10]. These giant outbursts have been modeled in [11].
- **S5 0716+71** was seen flaring in GeV, optical and radio bands during two periods, September 7-13, 2007 and Oct 19-29, 2007 [12].

B. Method and Results

We tested two methods to search for neutrino flares: the first case (hereafter the ”box method”), uses a pdf which counts only events which fall inside the selected time window:

$$T_i = \frac{H(t_{max} - t_i)H(t_i - t_{min})}{t_{max} - t_{min}}, \qquad (4)$$

where H is the Heaviside step function, and t_{min} and t_{max} are fixed from MWL data. The second case is to find a best-fit Gaussian to describe the neutrino emission, fitting the mean of the flare and its duration inside the selected time window. The time factor in the source term will be:

$$T_i = \frac{1}{\sqrt{2\pi}\sigma_t} e^{-\frac{|t_i - t_0|^2}{2\sigma_t^2}} \qquad (5)$$

where t_0 is the peak emission and σ_t is the width. The Gaussian search method yields more information about the flare, such as width and time of the peak of the emission, and also can use events outside of the time window. To focus the search on correlation with photon emission instead of an all-year search, we confined the mean to the time window, and the sigma can not be longer than the time window. The Gaussian introduces two additional parameters to fit, while the box method has no additional parameters over the time-integrated search.

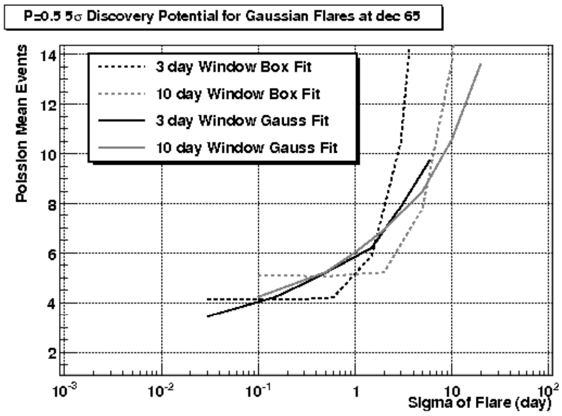

Fig. 3. Comparison of the box and Gaussian method for the flare search. The mean number of events needed for a $5-\sigma$ detection is plotted against the width of neutrino emission.

To compare the two methods, we generated signal events with Gaussian time distributions of different widths to add to scrambled data. Our figure of merit is the minimum flux required for 50% probability of 5σ discovery. We find the box method outperforms the Gaussian unless the FWHM of the signal function is less than 10% or greater than 110% of the width of the time window. We show the discovery potential curves for time windows of 3 and 10 days in Fig. 3. We also tested the possibility that the time window we chose based on MWL information is not centered on a neutrino flare by injecting events with an offset in the window, still finding a region where the box requires fewer events for discovery. Hence the box method, which performs better than the Gaussian method in a broad part of the signal parameter space was selected for providing the final p-values.

We found that 5 of 7 flares we examined were best fit by 0 source events, while S5 0716+71 and 1ES 1959+650 each showed one contributing event during a flare. Considering that we looked at 7 flares, the post trials p-value is 14% for the most significant result, the 10 day flare of S5 0716+71. This value is compatible with background fluctuations.

Source	Alert Ref.	Time Window	p-value
1ES 1959+650	[6]	MJD 54428-54433	1
1ES 1959+650	[7]	MJD 54435.5-54440.5	0.08
3C 454	[8]	MJD 54305-54311	1
3C 454	[9]	MJD 54416-54426	1
Cyg X-1	[10]	MJD 54319.5-54320.5	1
S5 0716+71	[12]	MJD 54350-54356	1
S5 0716+71	[12]	MJD 54392-54402	0.02

TABLE II
FLARE LIST: SOURCE NAME, REFERENCES FOR THE ALERT, INTERVAL IN MODIFIED JULIAN DAY, PRE-TRIAL P-VALUE.

V. Future Developments: Analysis Based on Long Light Curves

With the advent of Fermi, long and regularly sampled high energy γ-ray light curves will be available soon. The Fermi public data [13] already provide a first glimpse of the variable behavior of bright sources and the quality of the data. We plan to analyze Fermi light curves using the method described in [14]. Following this approach, the analysis of long light curves will provide:

- A systematic selection of flaring periods: until now the selection of flaring periods is biased because detections are often triggered by alerts. The monitoring of the sky provided by Fermi will eliminate this.
- A systematic criterion to define the threshold for a flare: once enough data will be accumulated, the flare statistics will provide a characteristic level and a standard deviation. With a safe 3σ threshold, flaring periods cannot be confused with intrinsic fluctuations of the detector and can be selected uniformly across the entire period considered.
- The possibility to select more than one flare in the same light curve, to estimate the frequency of the high states.
- A non-parametric time dependent signal pdf.

Our analysis of long Fermi light curves is still in development and for the moment limited by the relatively short duration of the Fermi data taking. We illustrate the method using the light curve collected by RXTE-ASM for Mkn 421 (Fig. 4). About 10 years of RXTE-ASM data are analyzed in order to extract a characteristic level of the source and determine flaring periods, as in [14]. For example here the threshold for flaring has been fixed at the 3σ level that corresponds to 1.7 RXTE/ASM count/sec. Interpreting periods selected above this level with the Maximum Likelihood Block algorithm provides the time dependent pdf (see Fig. 5).

While the rate of events observed in IceCube is approximately stable over timescales of a few days, the variability of the background has to be considered if longer periods are tested. The main source of variations of the observed event rates are changes in the detector uptime. These will be implemented in the description of the background.

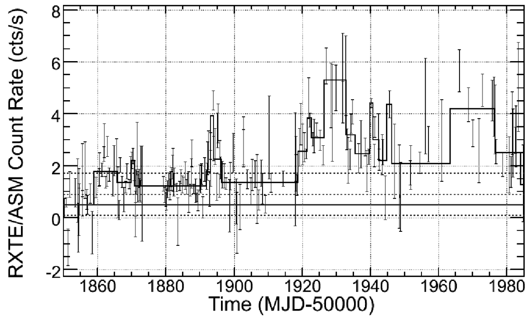

Fig. 4. Subperiod of Mkn 421 light curve collected by ASM/RXTE for illustration of the method.

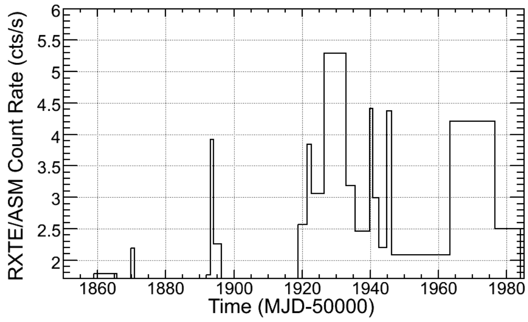

Fig. 5. The time pdf resulting from application of the 3σ threshold described in the text to the Mkn 421 light curve.

VI. Conclusions

We have presented the results of a time dependent analysis of the IceCube 22 string data sample. We searched for a periodic time structure of neutrinos from binary systems, and neutrinos in coincidence with high flux states from sources for which other experiments issued alerts. Results in all cases were consistent with background fluctuations. We also provide insight on how MWL information may in the future be directly used to create a time pdf to analyze correlations of photon and neutrino emission.

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