Searches for Time-Variable Neutrino Point Sources with the IceCube Observatory

THE ICECUBE COLLABORATION[1]
[1] *See special section of these proceedings.*

Abstract: We present searches for time-dependent emissions of neutrinos in the entire sky using the data collected between April 2008 and May 2010 with 40 and 59 strings of IceCube. An all-sky search is performed searching for any clustering of events in space and time. In the northern sky the sample is mainly atmospheric neutrinos, while in the southern sky the sample is dominated by atmospheric muons. In order to reduce the penalty of trials we also perform a search based on flares of AGNs observed by other experiments, using lightcurve information from bands where comprehensive coverage is available. Results from the 40-string detector are presented in this paper, while those from the 59 string detector will be presented at the conference.

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1 Introduction

The IceCube Neutrino Observatory is a kilometer-scale detector located at the geographic South Pole. Beneath the glacial surface, IceCube is composed of 5160 optical modules (DOMs) deployed on 86 vertical strings between 1450 and 2450 m to detect and reconstruct high energy neutrino-induced charged leptons. The main science goal of the IceCube experiment is the detection of astrophysical neutrino sources, which will help identify the origins of the highest energy cosmic rays.

Muons passing through the detector emit Čerenkov light allowing reconstruction with median angular resolution of less than 1° for > 10 TeV energy muons in the 40 and 59-string configurations.

Time-dependent analyses aim to reduce the background of atmospheric neutrinos and muons by searching over smaller time scales around a period of interest. The searches discussed in this paper are about a factor of four more powerful than time-integrated searches for flares with duration $\leq$ 100 s. In this paper we describe the addition of a time dependent term to the standard searches for steady emission of neutrinos presented in [1] [2]. We apply this term in searches for neutrino emission from an all-sky generic time-dependent search and from a catalogue of sources with photon flares occurring when IceCube was taking data in its 40 and 59-string configurations.

2 Time Dependent Point Source Searches

An unbinned maximum likelihood ratio method which models the data as a mixture of signal and background has been used for the search for point sources of neutrinos in IceCube [3]. We use the angular and energy distribution of events as information to characterize the signal with respect to the background. Astrophysical sources of neutrinos will cluster near the object and are expected to have a power-law energy spectrum harder than that measured of the atmospheric backgrounds [4]. An energy estimator is used based on the photon density along each reconstructed muon track. The atmospheric background has a roughly constant rate in time, but sources such as Active Galactic Nuclei exhibit significant variability in photon flux states, allowing for tests aimed at additional background rejection. The analysis returns a best-fit number of signal events and spectral index, as well as other free parameters from the time-dependent terms.

The IceCube 40-string data at analysis level consists of 36,900 selected events, 14,121 are upward-going neutrino candidate events and 22,779 are downward-going, mainly PeV energy muons from atmospheric air showers [1]. The 59-string data at analysis level consists of 107,569 selected events, 43,339 of which are upward-going neutrino candidates, and 64,230 are in the downward-going region [2]. The data used in this analysis were collected over 724 days of livetime between April 5, 2008 and May 31, 2010, corresponding to 92% of all data taken during that period. Selection cuts for the final sample are based on the quality of the reconstruction, such as the angular uncertainty of the track reconstruction, and on other variables such as the number of DOMs hit by the direct Čerenkov light produced by muons. These variables help reject misreconstructed events.

The signal probability distribution function (pdf) is:

$$S_i = S_i^{space}(\mid \vec{x}_i - \vec{x}_s \mid, \sigma_i) S_i^{energy}(E_i, \theta_i, \gamma_s) S_i^{time} \quad , \tag{1}$$

where σ_i is the reconstructed angular uncertainty of the event [5], $\mid \vec{x}_i - \vec{x}_s \mid$ the angular separation between the reconstructed event and the source, $S_i^{energy}(E_i, \theta_i, \gamma_s)$ is the energy pdf with the event energy E_i, zenith angle θ_i, and spectral index γ_s, which is built in 22 zenith bands to account for declination dependence of the background. S_i^{time} is the time pdf of the event. The background pdf is given by:

$$B_i = B_i^{space}(\theta_i, \phi_i) B_i^{energy}(E_i, \theta_i) B_i^{time}(t_i), \tag{2}$$

where $B_i^{space}(\theta_i, \phi_i)$ is the background event density (a function of the azimuth ϕ_i and zenith θ_i of the event), $B_i^{energy}(E_i, \theta_i)$ is the zenith-dependent energy distribution of the background, and $B_i^{time}(t_i)$ the inverse of the livetime, reflecting the fact that the probability density functions are normalized to one and the background rate is essentially flat in time. The background pdf is determined using the data, and the final p-value for each analysis is obtained by comparing equivalent experiments scrambled in time and right ascension to actually observed data.

3 All-Sky Time Scan

We perform a scan for any significant excess with respect to background over all time scales (from sub-seconds to a full year) over the entire sky. Since this analysis finds events clustered in time, independent scans are performed using the 40-string (April 5, 2008 to May 20, 2009) and 59-string (May 20, 2009 to May 31, 2010) samples. For flares shorter than ~100 days, this provides a better discovery potential for the time-dependent hypothesis than a time-integrated analysis. In principle short bursts can be discovered at a 5σ threshold with only two events if they occur near enough in time. An advantage of an untriggered search such as this is the ability to probe all emission scenarios, including neutrino emission without any observed counterpart in the electromagnetic spectrum.

This analysis method was developed and tested using a simulation of a generic km^3 neutrino detector in [6], and has been adapted for use with a detector with non-uniform acceptance in zenith and azimuth and dead time [7]. The time-dependent probability density function for this search is a Gaussian function, with its mean and width as free parameters, returning the most significant flare from a particular direction. The method is applied as an all-sky scan over a 0.5°x 0.5° grid (smaller than the typical event angular uncertainty) in right ascension and declination, scanning for flares of all durations from 20 μs (the minimum time separation between events) to 150 days. The final result is the set of best fit parameters from the location with the strongest deviation from background.

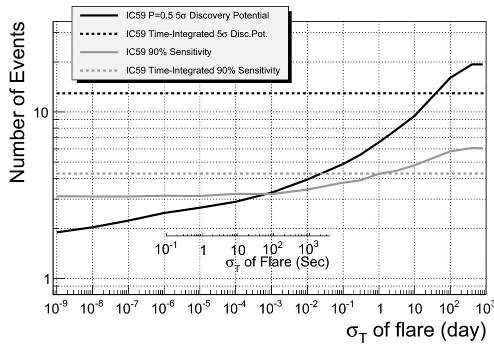

Figure 1: The 50% 5σ discovery potential and 90% sensitivity in terms of the mean number of events for a fixed source at $+16^o$ declination with the 59-string detector. The number of events for the sensitivity and discovery potential for the time-independent search are also shown. Flares with a σ_T of less than 40 days, or a FWHM of less than roughly 100 days during the 59-string data taking period, have a better discovery potential than the steady search.

3.1 40-String Results

Using the 40-string data, the location which deviates most from background is found at (RA,Dec)=(254.75°, +36.25°), and is presented in [7]. Two events are found (2.0° apart in space and 22 seconds in time), with a best-fit spectrum γ of 2.15 (with uncertainty of $\pm$0.4), mean of the flare T_o of MJD 54874.703125 and width σ_T of 15 seconds. A clustering of greater significance is seen in 56% of scrambled skymaps, which is consistent with a fluctuation of the background. The result of the scan with 59-strings data will be presented at the conference.

4 Triggered Search for Flares

When there is specific timing information about the photon activity of an astronomical object, that information can be used to reduce the background. For triggered sources, the focus is on objects such as blazars, which exhibit variability on timescales of hours to weeks. When flares are seen with comprehensive coverage, flux measurements are made on a regular basis and this continuous lightcurve can be used to define the activity at any point in time as low to high. This improves the ability to define periods of high flux state with a clear beginning and end. The assumption is that photon and neutrino emissions experience heightened states simultaneously. This analysis utilizes 1-day binned lightcurves from the Fermi LAT. Results for 40-string data are presented in [7], while at the conference results including the 59 string period will be shown.

4.1 Method and Expected Performance

Sources for this search were selected considering alerts during the 40 and 59-string data taking periods for sources in outburst $> 1.5 \times 10^{-6}$ photons/s/cm^2. Sources with flares in the 40-string period (April 5, 2008 to May 20, 2009) are listed in table 1. A Maximum Likelihood Block (MLB) algorithm [8][9] is used to de-noise the lightcurves by iterating over the data points to select periods from the lightcurves which are consistent with a constant flux, taking statistical errors into account. The hypothesis is that the neutrino emission follows the lightcurve, but only when the photon flux goes above a certain threshold F_{th}. By looking only at these high states the atmospheric background is largely reduced. The value of F_{th} is used as a free parameter, finding the value of the threshold which maximizes the significance of the data. This method is designed to avoid any penalty from making an incorrect *a priori* choice on a flaring threshold, which is larger than the effect of one additional degree of freedom.

$F(t_i)$ is defined as the value of the denoised light curve at t_i and F_{th} is the flux threshold below which no neutrino emission is assumed (i.e. S_i^{time}=0 if $F(t_i) \leq F_{th}$). In the case of $F(t_i) \geq F_{th}$, the probability of neutrino emission is assumed to be proportional to the flux level above that threshold:

$$S_i^{time} = \frac{(F(t_i) - F_{th})}{N_f}; \quad (3)$$

where the normalization factor N_f is the integral of the denoised light curve above the threshold. Allowing a lead or lag of up to 50 days was also tested. This resulted in a markedly higher number of events for discovery, so we constrained the neutrinos to come within $\pm$ 1 day of the photons.

4.2 Results

The results from all sources tested during the 40-string data-taking are listed in table 1. The most significant source from the 40-string data-taking period is PKS 1502+106, which has a pre-trial p-value of 5%. With the method, we find one high-energy event during the August 2008 flare. The post-trial p-value is 29%, which is compatible with background fluctuations. Results extending the lightcurves and adding the 59-strings data will be presented at the conference.

5 Conclusion

We have analyzed data from the IceCube observatory from the season 2008-9 when the detector consisted of 40 strings. The all-sky scan over all directions finds that the most significant cluster of events is separated in time by 22 s and in space by 2° and has a trial-corrected p-value of 56%. The most significant observation of a flare from catalogues compiled using Fermi-LAT and IACT alerts during the 40-string configuration data taking is PKS 1502+106, with a p-value of 29% after trials. The results of time-dependent searches including the IceCube 59-string data will be presented at the conference.

Source	pre-trial p-value	Threshold (10^{-6} cm^{-2} s^{-1})	Duration above threshold (days)
PKS 1510-089	—	0	282
3C 66A/B	0.47	0.675	57
3C 454.3	0.20	9.47	2.5
PKS 1454-354	—	0	282
3C 279	0.47	2.34	6
PKS 0454-234	—	0	282
PKS 1502+106	0.049	3.13	8
J123939+044409	—	0	282

Table 1: Sources tested with the 40 string data and pre-trial p-values for the flare search with continuous lightcurves. In the event of an underfluctuation no p-value is calculated. The overlap between the Fermi public release data and the 40-string data taking period is 282 days, that being the maximum duration of the lightcurve above F_{th}.

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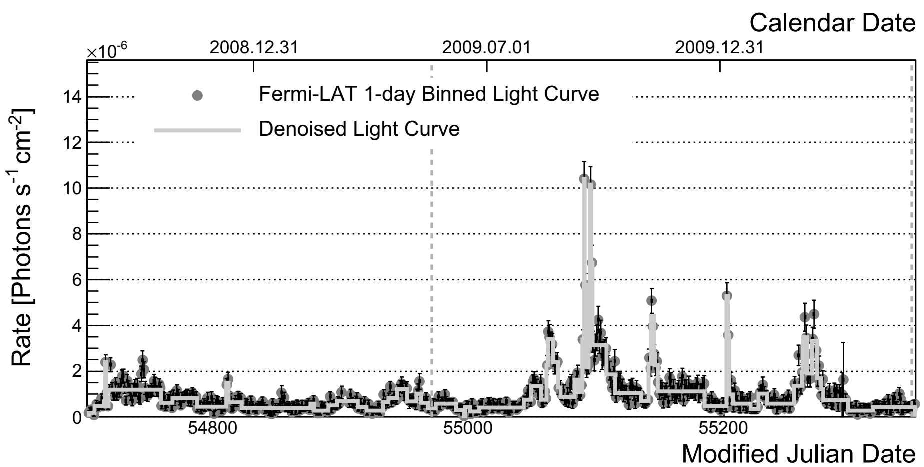

Figure 2: An example of the one-day binned Fermi lightcurve (gray points, with statistical errors) and denoised lightcurve (light gray solid line) for the blazar 3C273. The lightcurve begins here when Fermi science operations began, the time axis continues until the end of the 59-string data taking period.