Optical follow-up program of IceCube multiplets - testing for soft relativistic jets in Core-collapse Supernovae

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Abstract: Transient neutrino sources such as Gamma-Ray Bursts (GRBs) and Supernovae (SNe) are hypothesized to emit bursts of high-energy neutrinos on a time-scale of $\lesssim 100\,\mathrm{s}$. To increase the sensitivity to detect those neutrinos and identify their sources, an optical follow-up program for neutrinos detected with the IceCube observatory has been implemented. If a neutrino multiplet, i.e. two or more neutrinos from the same direction within 100 s, is found by IceCube a trigger is sent to the Robotic Optical Transient Search Experiment, ROTSE. The 4 ROTSE telescopes immediately observe the corresponding region in the sky in order to detect an optical counterpart to the neutrino events of IceCube. Data from the first year of operation of the optical follow-up program have been searched for a signal from supernovae. No statistically significant excess in the rate of neutrino multiplets has been observed and further no coincidence with an optical counterpart was found during the first year of data taking. This allows us to restrict current models predicting a high-energy neutrino flux from soft jets in core-collapse SNe. For the first time a stringent limit on the hadronic jet production in core-collapse SNe is derived.

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DOI: 10.7529/ICRC2011/V04/0445

Keywords: neutrinos, supernovae, gamma-ray bursts

1 Introduction

High-energy astrophysical neutrinos are produced in proton interactions of charged cosmic rays with ambient photon or baryonic fields (for reviews see [1]). Acceleration of protons to very high energies takes place in astrophysical shocks. Neutrinos escape the acceleration region and propagate through space without interaction, while protons are deflected in magnetic fields and no longer point back to their source. Unlike gamma-rays, neutrinos are solely produced in hadronic processes and could therefore reveal the sources of the highest energy charged cosmic rays. Gamma-ray bursts could provide the environment and the required energy to explain the production of the highest energy cosmic-rays and hence are a plausible candidate. Recent observations imply a common physical origin of long GRBs and core-collapse supernovae (CCSNe): a massive stellar explosion (see [2] for a review). According to the collapsar model [3], long GRBs (duration $\gtrsim 2\,\mathrm{s}$) have their origin in the collapse of a massive, rapidly rotating star into a black hole surrounded by an accretion disk. Relativistic jets with Lorentz boost factors of 100-1000 form along the stellar axis. This GRB-SN connection gives rise to the idea that GRBs and SNe might have the jet signature in common and a certain fraction of core-collapse SNe might host soft relativistic jets. SN jets are suggested to be equally energetic and more baryon-rich, hence they are only mildly relativistic. Such soft relativistic jets would become stalled in the outer layers of the progenitor star, leading to essentially full absorption of the electromagnetic radiation emitted by the jet and at the same time an efficient production of high-energy neutrinos [4, 5]. This motivates a search for neutrino emission, as neutrinos would be able to escape from within the star.

The IceCube neutrino detector, located at the geographic South Pole, is built to detect high-energy astrophysical neutrinos [6]. So far GRB neutrino searches have been performed offline on AMANDA [7] and IceCube [8] data, triggered by gamma-ray satellite detections. Furthermore, a dedicated search for a neutrino signal in coincidence with the observed X-ray flash of SN 2008D has been conducted by IceCube [9] in order to test the soft jet scenario for CCSNe. Neither the GRB nor the SN neutrino searches led to a detection yet, but set upper limits to the possible neutrino flux.

Early SN detections, as in the case of SN 2008D, are very rare since X-ray telescopes have a limited field of view. However, neutrino telescopes cover half of the sky at any time. If neutrinos produced in soft relativistic SN jets are detected in real time, they can be used to trigger follow-up observations [10]. This is realized with the optical follow-up program presented here. Complementary to the offline

searches, the optical follow-up program is an online search independent of satellite detections. It is sensitive to transient objects, which are either gamma-dark or missed by gamma-ray satellites. In addition to a gain in significance, the optical observations may allow to identify the transient neutrino source, be it a SN, GRB or any other transient phenomenon producing an optical signal. Hence it enables us to test the plausible hypothesis of a soft relativistic SN jet and sheds light on the connection between GRBs, SNe and relativistic jets.
In order to implement the optical follow-up program an online neutrino event selection was developed at the neutrino detector IceCube. The data are processed online by a computer farm at the South Pole. A multiplicity trigger selects neutrino burst candidates and the directional information is transferred to the four ROTSE telescopes, which start the follow-up immediately and continue observations for several days. The obtained optical data are analyzed in order to search for an optical supernova counterpart.

2 IceCube

The IceCube neutrino telescope has been under construction at the geographic South Pole since 2004 and was completed in the Antarctic summer of 2010/11. It is capable of detecting high energy neutrinos with energies above 100 GeV and is most sensitive to muon neutrinos within the energy range from TeV to PeV. High-energy muon neutrinos undergoing charged current interactions in the ice or the underlying rock produce muons in neutrino-nucleon interactions. The muon travels in a direction close to that of the neutrino and emits Cherenkov light. The deep ultra clear Antarctic ice is instrumented with light sensors thus forming a Cherenkov particle detector. After its completion it comprises a volume of $1\,\text{km}^3$ with 5160 digital optical modules (DOMs) attached to 86 vertical strings at a depth of 1450 m to 2450 m [6]. Each DOM consists of a 25 cm diameter Hamamatsu photomultiplier tube (PMT) and supporting hardware inside a glass pressure sphere. Here we present the analysis of the data taken from the start of the follow-up program on 2008/12/16 to 2009/12/31. Initially 40 IceCube strings were taking data. In May 2009 an additional 19 strings were included. This corresponds to an uptime of 121 days with 40 and 186.4 days with 59 strings. In the following the deployment stages will be referred to as IC40 and IC59.

2.1 Online System

In order to rapidly trigger optical telescopes the first online analysis of high-energy neutrinos detected by IceCube was developed and implemented. Unlike in the offline analyses, which are performed on an entire dataset (usually ~ 1 year of data) with time consuming reconstructions on a large computer cluster, the data are processed online by a computer cluster at the South Pole. The processing includes event reconstruction and basic event selection. The first year of data presented here was taken with a latency of 6-8 h. With the start of operations with 79 strings the processing was upgraded reducing the latency to a few minutes. After the parallel processing the data arrive on a dedicated machine (analysis client), where a sophisticated event selection is applied based on the reconstructed event parameters. A multiplicity trigger selects neutrino burst candidates (see section 2.2). No further reconstruction algorithms need to be applied at the analysis client allowing a very fast filtering of the events ($\ll 1$ s). The directional information is transferred to Madison, Wisconsin, via the Iridium satellite network within about 10 s. From there the message is forwarded to the four ROTSE telescopes via the internet through a TCP-socket connection for immediate follow-up observations. The stability and performance of the online system is constantly monitored in order to allow a fast discovery of problems. To achieve this, test alerts are produced at a much higher rate (~ 100 test alerts per day compared to 25 real alerts per year) by the same pipeline and are also send to the North. Their rate and delay time distributions are monitored using an automatically generated web page.

2.2 Neutrino Event Selection

The background in a search for muon-neutrinos of astrophysical origin can be divided into two classes. One consists of atmospheric muons, created in cosmic ray air showers, entering the detector from above. The other is given by atmospheric neutrinos which have their origin in meson decays in cosmic ray air showers. The expected neutrino signal according to the soft jet SN model can be calculated as a function of two model parameters: the boost Lorentz factor Γ and the jet energy E_{jet} [9]. Signal events are simulated following the predicted neutrino flux spectrum in order to develop and optimize selection criteria to distinguish signal and background events. Restricting the search to the Northern hemisphere and imposing requirements on the event reconstruction quality (e.g. the number of hits with small time residual or the likelihood of the reconstruction) allows a suppression of the mis-reconstructed muon background. To suppress the background of atmospheric neutrinos, which we cannot distinguish from the soft SN neutrino spectrum, we require the detection of at least two events within 100 s and an angular difference between their two reconstructed directions of $\Delta\Psi \leq 4°$. The choice of the time window size is motivated by the jet penetration time. The observed gamma-ray emission from long GRBs has a typical length of 50 s, which roughly corresponds to the time for a highly relativistic jet to penetrate the stellar envelope. The angular window $\Delta\Psi$ is determined by the angular resolution of IceCube and was optimized along with the other selection parameters. The final set of selection cuts has been optimized in order to reach a multiplet rate of ~ 25 per year corresponding to the maximal number of alerts accepted by ROTSE. The final data stream consists of 37% (70%) atmospheric neutrinos for IC40 (IC59). Combining the neutrino measurement with the optical measurement allows the cuts to be relaxed yielding a larger background contamination and at the same time a higher signal passing rate. A doublet is not significant by itself, but may become significant when the optical information is added. Each multiplet is forwarded to the ROTSE telescopes. The doublet direction is calculated as a weighted mean from the single reconstructed directions comprising the multiplet. The single events are weighted with $1/\sigma^2$, where σ is the reconstruction error estimated by the paraboloid fit, which fits a paraboloid to the likelihood landscape around the minimum defined by the best fit. The resolution of the doublet direction is $\sim 0.8°$.

3 Search for Optical Counterparts

The IceCube multiplet alerts are forwarded to the robotic optical transient search experiment (ROTSE), which consists of four identical telescopes located in Australia, Texas, Namibia and Turkey [11]. The telescopes stand out because of their large field of view (FoV) of $1.85° \times 1.85°$ and a rapid response with a typical telescope slew time of 4 sec to move the telescope from the standby position to the desired position. The telescopes have a parabolic primary mirror with a diameter of 45 cm. To be sensitive to weak sources no bandwidth filter is used. ROTSE is most sensitive in the R-band (~ 650 nm). The wide field of view is imaged onto a back-illuminated thinned CCD with 2048×2048 $13.5\,\mu$m pixels. For a 60 sec exposure at optimal conditions the limiting magnitude is around $m_R \approx 18.5$, which is well suited for a study of GRB afterglows during the first hour or more and SN light curves with peak magnitude ≤ 16. The corresponding FWHM (full width at half maximum) of the stellar images is less than 2.5 pixels (8.1 arcseconds). Observations are scheduled in a queue and are processed in the order of their assigned priority. IceCube triggers have second highest priority after GRB follow-ups triggered by the GRB Coordinate Network (GCN).

Once an IceCube alert is received by one of the telescopes, the corresponding region of the night sky will be observed within seconds. A predefined observation program is started: The prompt observation includes thirty exposures of 60 seconds length. Follow-up observations are performed for 14 nights. This was extended on 2009/10/27 to 24 nights, with daily observations for 12 nights and then observations during every second night up to day 24 after the trigger was received. Eight images with 60 seconds exposure time are taken per night. The prompt observation is motivated by the typical rapidly decaying light curve of a GRB afterglow, while the follow-up observation of 14 (or 24) nights permits the identification of a rising SN light curve. In the initial phase with IC40 and IC59, the online processing latency of several hours made the search for an optical GRB afterglow unfeasible. We therefore focus on the SN light curve detection in the ROTSE data.

Image correction and calibration are performed at the telescope sites. The images of each night are combined in order to obtain a deeper image. A reference image is subtracted from each combined image using the algorithm developed by [12]. As deep images are usually not available for the positions we would like to observe, we initially choose the deepest image of our observing sequence as the reference image. In 40% of the alerts we took another deep image roughly one year later. Both SN light curves and GRB afterglows would have faded after a few weeks, and would not be present in the newly taken reference image.

All extracted objects found in the subtracted images are candidates for variable sources. However, bad image quality, failed image convolution, bad pixels and other effects frequently cause artifacts in the subtraction process, requiring further selection of the candidates. A candidate identification algorithm including a boosted decision tree is applied to classify sources according to geometrical and variability criteria. The final candidates are summarized on a web page and are inspected visually by several trained persons, who have to classifiy the candidate as a SN, a variable star or a subtraction artifact. SN candidate identification by the human eye works well as shown in the galaxy zoo SN project [13]. The visual scanning was performed by three individual persons to ensure no good candidate was missed and to avoid false positives.

4 Results

This paper presents the results from the analysis of data taking in the period of 2008/12/16 to 2009/12/31. Table 1 shows the number of detected and expected doublets and triplets for the IC40 and the IC59 datasets as well as the number of detected and expected optical SN counterparts. The IceCube expectation based on a background only hypothesis was obtained from scrambled datasets. To correctly incorporate detector asymmetries, seasonal variations and up-time gaps we used the entire IC40 and IC59 datasets and exchanged the event directions randomly while keeping the event times fixed. The number of doublets shows a small excess, which corresponds to a $2.1\,\sigma$ effect and is thus not statistically significant. The expected number of randomly coincident SN detections, $N_{\mathrm{SN}}^{bg} = 0.074$, is based on an assumed core-collapse SN rate of 1 per year within a sphere with radius 10 Mpc, i.e. $2.4 \cdot 10^{-4}\,\mathrm{y}^{-1}\,\mathrm{Mpc}^{-3}$, and a Gaussian absolute magnitude distribution with mean of -18 mag and standard deviation of 1 mag for CCSN [14]. In total 31 alerts were forwarded to the ROTSE telescopes. Five could not be observed be-

Table 1: measured and expected multiplets

	SN	Doublets		Triplets	
		IC40	IC59	IC40	IC59
measured	0	15	19	0	0
expected	0.074	8.55	15.66	0.0028	0.0040

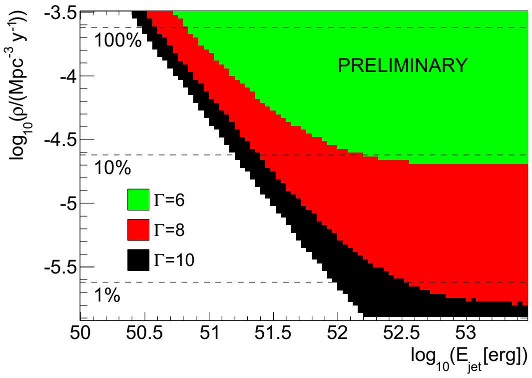

Figure 1: Limits on the choked jet SN model [5] for different boost Lorentz factors Γ as a function of the rate of SNe with jets ρ and the jet energy $E_{\rm jet}$ (colored regions are excluded at 90% CL). Horizontal dashed lines indicate a fraction of SNe with jets of 100%, 10% or 1%.

cause they were too close to the sun. For two alerts no good data could be collected. Seven alerts were discarded because the corresponding fields were too close to the galactic plane and hence too crowded. Thus 17 good optical datasets remained for the analysis. The data were processed as described above. No optical SN counterpart was found in the data.

We obtain the confidence level for different combinations of SN model parameters [5] by using a pre-defined test statistic based on a likelihood function. The limit is calculated for the jet boost Lorentz factors $\Gamma = 6, 8, 10$ as a function of the rate of SNe with jets ρ and the jet energy $E_{\rm jet}$. Systematic errors related to the simulated neutrino sensitivity and the SN sensitivity are included in the limit calculation. The 90% confidence regions for each Γ-value are displayed in the $E_{\rm jet}$-ρ-plane in figure 1 (colored regions are excluded at 90% CL). Including the optical information into the limit calculation improved the limit and allows tests of 5-25% smaller CCSN rates. The largest improvement is obtained for small jet energies and large CCSN rates. The most stringent limit can be set for high Γ-factors. Less than 4.2% of all SNe have a jet with $\Gamma = 10$ and a typical jet energy of $E_{\rm jet} = 3 \cdot 10^{51}$ erg. This is the first limit on CCSN jets using neutrino information.

5 Summary and Outlook

The optical follow-up program of IceCube neutrino multiplets realized by the four ROTSE telescopes proves the feasibility of the program. The technical challenge of analyzing neutrino data in real time at the remote location of the South Pole and triggering optical telescopes has been solved. First meaningful limits to the SN slow-jet hypothesis could be derived already after the first year of operation. Especially in cases of high boost Lorentz factors of $\Gamma = 10$ stringent limits on the soft jet SN model are obtained. Soderberg *et al.* [15] obtain an estimate on the fraction of SNe harboring a central engine from a radio survey of type Ibc SNe. They conclude that the rate is about 1%, consistent with the inferred rate of nearby GRBs. Our approach is completely independent and for the first time directly tests hadronic acceleration in CCSN, while the radio counterpart is sensitive to leptonic acceleration.

The volume of the IceCube detector has now increased to a cubic kilometer yielding a larger sensitivity to high-energy neutrinos. In addition the acquired uptime is growing continuously. The delay of processing neutrino data at the South Pole has been reduced significantly from several hours to a few minutes. This results in the possibility of a very fast follow-up and allows the detection of GRB afterglows, which fade rapidly below the telescope's detection threshold.

Because of the successful operation of the optical follow-up program with ROTSE, the program was extended in August 2010 to the Palomar Transient Factory (PTF) [16], which will provide deeper images and a fast processing pipeline including a spectroscopic follow-up of interesting SN candidates. Furthermore an X-ray follow-up by the Swift satellite of the most significant multiplets has been set up and started operations in February 2011 [17].

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