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Detecting GRBs with IceCube and optical follow-up observations

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Abstract: We present a summary of AMANDA results obtained in searches for neutrinos from Gamma-Ray Bursts (GRBs). Using simulations, we show how the IceCube detector, which is currently being constructed at the South Pole, will improve the sensitivity of the search. In order to improve the prospects for detections of gamma-ray dark bursts (e.g. choked bursts), as well as core collapse Supernovae (SNe), we discuss a novel follow-up scheme of high energy neutrino events from IceCube. Triggered by neutrino events from IceCube, a network of small optical telescopes is meant to monitor the sky for SNe rising lightcurves and GRB afterglows. The observing program is outlined and its status discussed.

Introduction

GRBs have been proposed as one of the most plausible sources of ultra-high energy cosmic rays [1] and high energy neutrinos [2]. In addition to being a major advance in astronomy, detection of high energy neutrinos from a burst would provide corroborating evidence for the acceleration of ultra-high energy cosmic rays within GRBs. It has been noticed that so-called long GRBs are often accompanied by SNe type Ib/Ic [3]. The prevalent interpretation is that the progenitors of these SNe and GRBs are very massive stars that undergo core collapse that leads to the formation of a black hole. The material accreted by the black hole can form highly relativistic jets which then produce the observed burst of γ-rays and accelerate particles to high energy. The connection between SNe and GRBs has inspired the speculation that a fraction of core collapse SNe which do not lead to GRBs may still be the source of TeV neutrinos [4].

For the purposes of establishing the sensitivity of IceCube to GRBs we will use the Waxman-Bahcall GRB [2] model as a benchmark. We will assume a flavor flux ratio of 1:1:1 at Earth motivated by neutrino oscillations. We use a flux normalization of 1.35×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 1 PeV at the Earth for all neutrino flavors combined, a break energy of 100 TeV and a synchrotron break energy of 10 PeV. Finally, we assume that the Waxman-Bahcall GRB model corresponds to 670 GRBs per year over the full sky resulting in an average neutrino fluence per burst of $F_{\rm burst} = 1.3 \times 10^{-5}$ erg/cm^2 for all flavors combined. However, it should be noted that fluctuations in the characteristics of GRBs, notably redshift and γ-ray fluence, lead to significant fluctuations in the expected number of neutrinos from burst to burst [5].

IceCube is a high energy ($E > 1\,\mathrm{TeV}$) neutrino telescope currently under construction at the South Pole [6]. When completed, the deep ice component of IceCube will consist of 4800 digital optical modules (DOMs) arranged in up to 80 strings frozen into the ice, at depths ranging from $1450\,\mathrm{m}$ to $2450\,\mathrm{m}$. Each DOM contains a photomultiplier tube and supporting hardware inside a glass pressure sphere. The total instrumented volume of IceCube will be $\sim 1\,\mathrm{km}^3$. The DOMs indirectly detect neutrinos by measuring the Cherenkov light from secondary charged particles produced in neutrino-nucleon interactions.

AMANDA-II [7], now integrated in IceCube as a sub-detector, was commissioned in the year 2000 and consists of a total of 677 optical modules. These are arranged on 19 strings with the sensors at depths ranging from $1500\,\mathrm{m}$ to $2000\,\mathrm{m}$ in a cylinder of $100\,\mathrm{m}$ radius. Its instrumented volume is about 70 times smaller than that of the deep ice component of IceCube.

The two main channels for detecting neutrinos with IceCube and AMANDA are the ν-induced muon and the ν-induced cascade channels. For the muon channel the detectors are mainly sensitive to up-going muons as the Earth can be used to shield against the much larger flux of down-going atmospheric muons. Searches for neutrinos from GRBs in the muon channel benefit from good angular resolution ($\sim 1^\circ$ for $E_\nu > 1$ TeV) and from the long range of high energy muons. For cascade channels the detectors are sensitive to all neutrino flavors through various interaction channels. Here, analyses benefit from good energy resolution (~ 0.1 in $\log_{10} E$) and from 4π sr sensitivity to high energy neutrinos. The number of expected detected events can be calculated by convoluting the neutrino flux Φ with the corresponding effective neutrino area A_ν^{eff}:

$$N_{\mathrm{evts}} = T \int \mathrm{d}\Omega \mathrm{d}E A_\nu^{\mathrm{eff}}(E,\theta)\frac{\mathrm{d}\Phi}{\mathrm{d}E}(E,\theta)\ , \quad (1)$$

where T is the observation time.

Searches for neutrinos in coincidence with GRBs have been conducted with the AMANDA detector in the muon and the cascade channels. The muon search was performed on over 400 bursts reported by BATSE and IPN3 between 1997 and 2003 [8]. Additionally, a dedicated search for neutrinos in coincidence with GRB030329 was performed [9]. Using the cascade channel, one analysis [10] focused on 73 bursts reported by BATSE in 2000 and another analysis searched for a statistical excess of cascade-like events during a rolling period of $1\,\mathrm{s}$ and $100\,\mathrm{s}$ for the years 2001-2003 [10]. So far no evidence for neutrinos from GRBs has been found. With the muon search the 90% c.l. limit set by AMANDA is 1.3 times higher than Waxman-Bahcall's prediction as defined above.

The main source of GRB data to be studied by IceCube will be GLAST, but also other satellites, e.g. Swift, will contribute. Since finding an unusually bright nearby GRB is key for the detection of neutrinos, the ideal satellite has a very large field of view (FoV). GLAST's FoV is $\sim$9 sr and Swift's $\sim$1.4 sr. In our calculations we assume a yearly detection rate of 200 GRBs by GLAST which are distributed uniformly over the sky. IceCube can be operated while being built. By the end of 2008 the accumulated exposure will be 0.75 km$^2\cdot$yr; 1.3 km$^2\cdot$yr by 2009 and 1.9 km$^2\cdot$yr by 2010. IceCube is currently taking data with 22 strings.

IceCube sensitivity to muon neutrinos

In order to calculate the sensitivity of the IceCube detector to muon neutrinos from GRBs, bursts are simulated uniformly distributed over the northern sky. Each burst is assumed to produce a muon neutrino fluence of $1/3\, F_{\mathrm{burst}}$. The muon neutrino effective area as a function of neutrino energy and zenith angle is obtained from a full Monte Carlo simulation including a detailed ice and detector simulation. Displayed in Fig.1 is the effective area at trigger level as a function of energy averaged over zenith angles above 90° (up-going neutrinos). Past searches with AMANDA [8] have shown that 25–75% efficiency can be obtained with respect to trigger level once selection criteria are applied to data in order to remove the down-going muon background. IceCube has the potential of even higher efficiency. Thus we consider trigger level effective area representative (upper limit) of what the detector will be able to achieve.

The narrow constraints on the position and the timing of neutrinos from a GRB combined with the good angular and time resolution of IceCube lead to a very low expected background. For this first sensitivity estimate we therefore assume a background free observation.

In the following we estimate the number of GRBs required to reach the GRB flux predicted by Waxman-Bahcall and exclude it at 99.73% C.L. (3σ). With the observation of no events and a mean expected background of zero events the Feldman-Cousins method [11] yields an event upper limit of 6.0. In order to reach this number about 70 bursts in the northern hemisphere must be observed which can be expected after about 1 year of operation of the full detector.

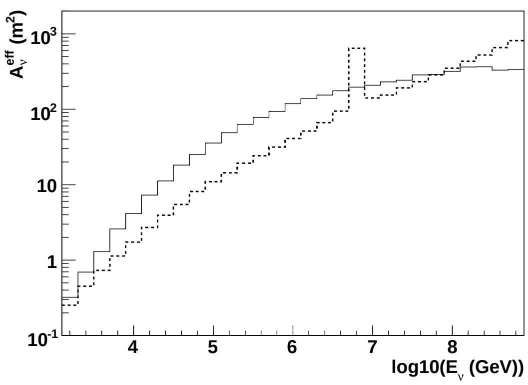

Figure 1: IceCube's effective neutrino area as a function of the neutrino energy at trigger level for ν_μ (solid) and ν_e (dashed). The ν_μ effective area is the average for neutrinos from the northern sky (2π sr) whereas that for ν_e is averaged over the whole sky (4π sr). The peak at 6.3 PeV is the Glashow resonance.

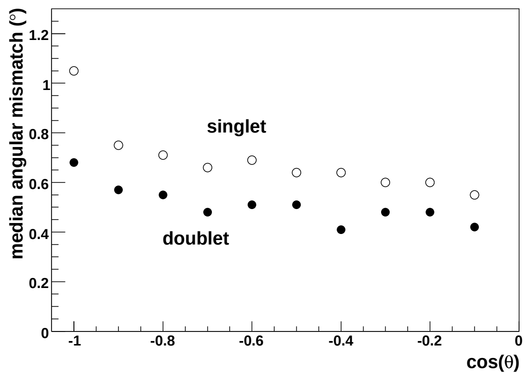

Figure 2: Median angular mismatch for single neutrino events and neutrino doublets (with $\Delta\Psi < 3°$). Quality cuts have been applied.

IceCube sensitivity to electron neutrinos

For ν_e-induced cascades the effective neutrino area $A^{\text{eff}}_{\nu_e}$ is calculated for a uniform distribution of ν_e and $\bar{\nu}_e$ over 4π sr. We have taken into account charged current and neutral current interactions as well as the Glashow resonance. The effective area, averaged over an equal mixture of ν_e and $\bar{\nu}_e$, can be seen in Fig. 1. As with the muon channel, the effective area presented here is at trigger level.

The narrow constraints on the timing of neutrinos from a GRB combined with the good cascade energy and time resolution of IceCube lead to a very low expected background. We calculate the sensitivity supposing a background free search.

In the following we estimate the number of GRBs required to reach the GRB flux predicted by Waxman-Bahcall and exclude it at 99.73% c.l. (3σ). With the observation of no events and a mean expected background of zero events the Feldman-Cousins method yields an upper limit of 6.0. In order to reach this number about 560 bursts must be monitored. This can be expected after almost 3 yr of operation of IceCube in coincidence with GLAST. Including the contributions from ν_μ and ν_τ-induced cascades would roughly double the number of expected events [10] [1] Thus the number of bursts required is ~ 280 or 1.5 yr of satellite coincident observations.

An optical follow-up for neutrino events

So far we have discussed the search for a neutrino signal in coincidence with a GRB identified through satellites. For the future, we plan to complement this by performing an automated optical follow-up observations of selected neutrino events from IceCube [12]. First, the direction of neutrinos detected with IceCube is reconstructed online and if energy or multiplicity pass a certain threshold, a notice is sent to a network of optical telescopes. Then, within minutes after reception of the notice, automated optical telescopes monitor the corresponding part of the sky. Transient objects are thereby identified, e.g. through detection of GRB afterglows (on a timescale of minutes to hours) or rising SNe light-curves (on a timescale of days). These multi-messenger observations significantly improve the discovery potential of IceCube by providing a chance to detect and identify the source of the high-energy neutrinos. In what follows, we discuss the IceCube neutrino-burst trig-

1. Given the improved capabilities of IceCube it may be possible to treat high energy ν_τ-induced events as a separate channel.

ger and the corresponding telescope requirements for the optical follow-up observations.

The rate of atmospheric ν_μ events observed in the full IceCube detector is too high to perform individual follow-up observations: the trigger rate of neutrinos with zenith angle $> 80^\circ$ will be $\sim 7\times 10^5$ events per year. After imposing quality cuts similar to those used in Ref. [13], the rate is $\sim 7\times 10^4$ per year but remains high. However, the background rate can be significantly reduced by triggering on multiplets, i.e. two or more neutrinos detected within a short time window, Δt, and within a spacial window, $\Delta\Omega$. Here Δt is determined by the typical burst duration. An adequate time scale which covers the duration of most GRBs and SNe models is 100 s. The optimal size $\Delta\Omega$ is determined by the pointing resolution of IceCube, which is of the order of one degree. Using simulation, the rate of doublets for a maximal angular separation of 3° as well as $\Delta t = 100$ s is 30 per year. This number is low enough that individual follow-up observations can be performed.

Once the alert will be issued, the corresponding part of the sky has to be searched for transient sources. By averaging the reconstructed directions of the neutrinos in a multiplet, one can improve the localization of the potential source. The median angular mismatch between the average and the true direction as a function of the declination band is shown in Fig. 2. The median angular mismatch is $0.5^\circ - 0.6^\circ$.

An optical telescope with a FoV of $2^\circ \times 2^\circ$ would cover more than 80 % of the IceCube's point spread function for doublets. Already now optical telescopes with such a FoV exist. For example, the ROTSE-III network consists of 4 fully automated telescopes, each with a 0.45 m diameter mirror and a $1.85^\circ \times 1.85^\circ$ FoV.

Conclusions

We have presented a preliminary summary of the capabilities of IceCube. With several search strategies in place, IceCube will be ready to discover a range of different phenomena related to GRBs, such as prompt emission of PeV neutrinos, precursor and afterglow neutrinos from GRBs and neutrinos from core-collapse SNe.

Within a few years IceCube will be able to detect the neutrino flux predicted by Waxman-Bahcall with high significance or set limits well below any current prediction. Follow-up observations with optical telescopes as suggested in this paper will further enhance and complement the satellite triggered searches by enabling IceCube to observe the potentially large fraction of bursts where no γ-ray signal is detected by satellites (dark GRBs). An optical follow-up program for IceCube will possibly be implemented in 2008.

Both in the case of detection or in the case of the derivation of an upper limit, the results from IceCube will boost our understanding of GRBs, one of the most puzzling phenomena in our universe, and contribute to the resolution of the mystery of the origin of cosmic rays at the highest energies.

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