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GAMMA-RAY BURST DETECTION WITH ICECUBE

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With their narrow emission window gamma-ray bursts (GRBs) are among the most promising objects for the first identification of high-energy cosmic neutrinos. If a considerable fraction of the ultra-high energy cosmic rays is indeed produced in GRBs, IceCube, which is now more than half-way completed, should be able to detect the associated neutrinos in the next few years. Furthermore, optical follow-up observations of neutrino multiplets will enhance IceCube's sensitivity to choked GRBs which do not produce a gamma-ray signal.

Keywords: Neutrino telescope; IceCube; gamma-ray bursts.

1. Introduction

Gamma Ray Bursts (GRBs) have been proposed as very 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 supernovae (SNe) of type Ib/Ic.[3] The prevalent interpretation is that the progenitor 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 gamma 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]

2. Current Status of Searches for Neutrinos from GRBs

The current best limits on neutrino emission during the prompt phase of GRBs, displayed in Fig. 1, come from the AMANDA-II neutrino telescope.[7] These limits were obtained in a search for muon neutrinos from 419 bursts[8] detected by BATSE between 1997–2003. The large number of bursts allowed to set an upper limit (90%

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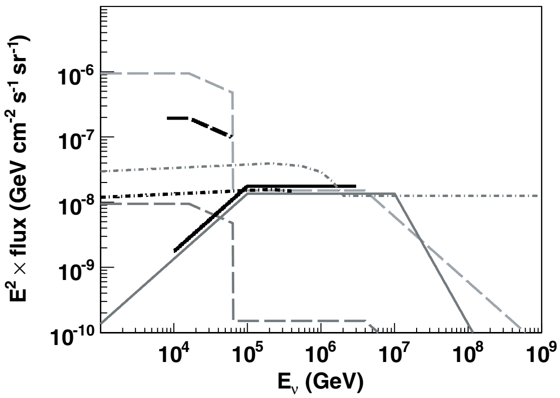


Fig. 1. GRB all-flavor neutrino flux predictions (gray) and final upper limits from AMANDA-II (black): Waxman–Bahcall[2] (solid), precursor for H-progenitors[5] (dashed), supranova[6] (dash-dotted). The light gray dashed line assumes that all SNe exhibit jets whereas in case of the dark gray dashed line jets are only produced in GRBs which also produce a gamma-ray signal. Note, that for this all-flavor plot the AMANDA-II muon neutrino limits from the publication[7] have been multiplied by a factor three.

C.L.) on the neutrino flux from GRBs only a factor 1.4 above the prediction from Waxman–Bahcall[2] and already a factor 0.92 below that of the supranova model[6] for the case that all GRBs have a SN remnant shell. In addition, a satellite-independent analysis in the cascade channel was performed[9] that looked for a clustering of events in time. The latter kind of searches have the advantage that they are also sensitive to so-called choked GRBs, where the jet gets stuck inside the envelope of the progenitor star and, hence, no gamma-ray signal is produced. The derived upper flux limit is significantly below the predicted neutrino flux from the precursor phase for the case that all SNe have a H-progenitor and exhibit these jets. This scenario is therefore highly disfavored.

With the nearing completion of the 60 times larger IceCube detector the search for neutrinos from GRBs enters into a new phase. In its final configuration IceCube will instrument a volume of about 1 km^3 of clear ice at depths between 1450 m and 2450 m below the geographic South Pole. Neutrinos are reconstructed by detecting the Cherenkov light from charged secondary particles, which are produced in interactions of neutrinos with the nuclei in the ice or bedrock. The optical sensors are photomultipliers, housed in pressure-resistant glass spheres (Digital Optical Modules, DOMs[10]), which are mounted on vertical strings. Each string consists of 60 DOMs with the final detector containing 80 strings. The completion of the detector construction is planned for the year 2011.

In case of satellite-based searches for neutrinos from GRBs, IceCube will mainly rely on the time and position information obtained with the Swift and Fermi satellites. Due to the different performance characteristics their burst population differs from that selected with the BATSE satellite, which was used by Waxman and

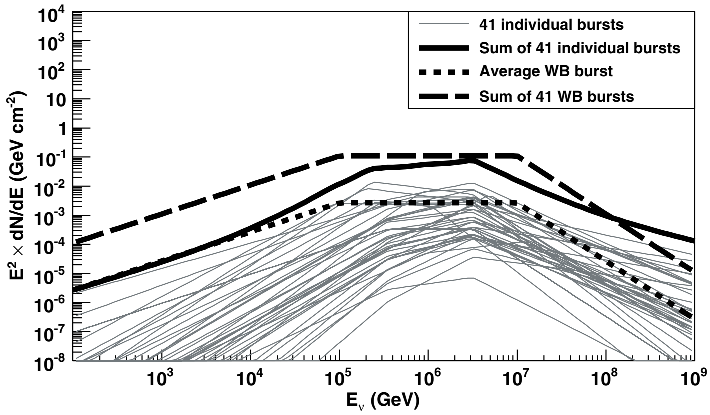


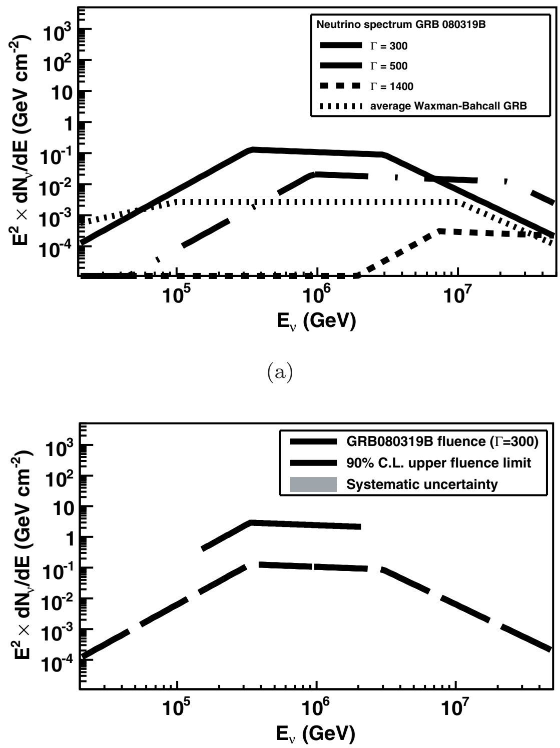
Fig. 2. Individual muon neutrino spectra for 41 bursts detected by satellites (mainly Swift) in 2007 and 2008. For comparison an average Waxman–Bahcall GRB is shown.

Bahcall to derive the GRB flux. Figure 2 compares the average Waxman–Bahcall GRB flux to individual fluxes of 41 bursts (detected mainly by Swift) which were calculated within the fireball model[11] using measured quantities like the gamma-ray spectrum. The visible differences demonstrate that an individual modeling of the neutrino fluxes for bursts detected by Swift and Fermi is necessary.

In general, the expected mean number of neutrinos in current and next-generation neutrino telescopes from an individual GRB is small. Therefore, usually stacking analyses are performed. Results from such an analysis of the IceCube 22-string data with 41 GRBs will soon be published. Exceptionally bright GRBs like GRB 080319B, however, might yield fluxes detectable by neutrino telescopes like IceCube. A calculation of the neutrino spectrum for this particular burst (see Fig. 3(a)) following Ref. 2 and using the measured burst parameters yielded an expected mean number of neutrinos in the 9-string IceCube detector, active at the time of the GRB, of ~ 0.1 assuming a jet Lorentz boost factor of $\Gamma = 300$.[12] However, the event number is sensitive to quantities that are not directly measured and therefore not very well known. For example, Fig. 3(a) shows the change in fluence if the Γ factor is 500 and 1400, respectively. The analysis of the IceCube data for GRB 080319B yielded no excess above the background.[12] The 90% C.L. limit on the fluence is about 22 times the calculated fluence (Fig. 3(b), $\Gamma = 300$). For IceCube with 80 strings, of $\mathcal{O}(1)$ events are expected to be observed from a similar burst making these rare events highly interesting also for future searches.

3. Outlook

Within the next years, IceCube, the first cubic-kilometer size neutrino telescope, will enter a phase with high potential for discovery. Especially, the search for neutrinos from GRBs is promising as the increased detector sensitivity combined with



(a)

(b)

Fig. 3. (a) Neutrino spectra for GRB 080319B for three different Γ factors of the jet. For comparison an average Waxman–Bahcall GRB is shown. (b) Upper IceCube limit on the muon neutrino fluence from GRB 080319B.

the expected large number of GRBs detected by satellites (100–150 per year in the northern hemisphere by Swift and Fermi) is sufficient to detect the neutrino fluxes predicted in several models[2,6] within the next years. In case no associated neutrinos are observed the obtained limits will allow to set stringent limits on models of neutrino production in GRBs. For example, the Waxman–Bahcall GRB model would be excluded by about a factor 10, disfavoring GRBs as the major sources of ultra-high energy cosmic rays.

But also satellite-independent searches will profit from the large gain in detection volume. Here, searches for core-collapse SNe with mildly relativistic jets that do not emerge from the envelope of the progenitor star are very promising. Models predict up to 30 neutrinos in the full IceCube detector from such a SN at 10 Mpc.[4,13] The significance of the observation of neutrinos from such an event can be enhanced by follow-up observations with optical telescopes which would detect the SN light curve. Such a system has been set up for IceCube.[14] It looks for spatial and temporal coincidences between neutrino candidates in the data and sends corresponding alerts to robotic optical telescopes that perform follow-up observations over several weeks. Overall, the coming years will be an exciting time for searches of neutrinos from GRBs with IceCube.

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