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DETECTING GAMMA-RAY BURSTS WITH ULTRA-HIGH ENERGY NEUTRINOS

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Gamma-ray bursts are candidate sources of ultra-high energy cosmic rays and neutrinos. While cosmic rays are scattered in the intervening magnetic field, neutrinos point back to their sources being charge neutral and make neutrino astronomy possible. Detection of ultrahigh energy neutrinos by future experiments such as ANITA, ANTARES, IceCube and RICE can provide useful information such as particle acceleration, radiation mechanism and magnetic field about the sources and their progenitors. Detection of ultrahigh energy neutrinos which point back to their sources may establish gamma-ray bursts as the sources of GZK cosmic rays.

1. Introduction

Gamma-ray bursts (GRBs) are arguably the sources of ultra-high energy (UHE) cosmic rays, with energies up to 3×10^{20} eV, and of UHE neutrinos which are yet to be detected. In the most popular models of GRBs, ultra-relativistic plasma jets, with bulk Lorentz factor $\Gamma_b \gtrsim 100$, are believed to drive the dynamics.[1] Protons and electrons are expected to gain UHE due to Fermi shock acceleration in the high magnetic field arising from colliding shells of material inside the jet. Synchrotron radiation and inverse Compton scattering of high energy electrons are likely to be responsible for the observed γ-rays. UHE protons, on the other hand, interact with γ-rays ($p\gamma \to \Delta^+ \to p\pi^+$) or cold baryons ($pp \to \pi^\pm, K^\pm$) to produce ν's through π, K and μ decay channels. Typically $p\gamma$ interactions dominate pp interactions in the GRB jets because of very high target photon density compared to baryon density. In the dense media which we discuss below, pp interactions may produce high energy ν's below the threshold energy of $p\gamma \to \Delta^+$. In general pp interactions produce more numerous low energy ν's than $p\gamma$ interactions do, thus improving the detection probability in the TeV-PeV energy range, where large neutrino Cherenkov detectors, such as IceCube, are most sensitive.[2]

We discuss two high energy neutrino flux models from GRBs. These neutrinos are additional to neutrinos from prompt γ-ray bright bursts and afterglows.[3,4,5] Upcoming detectors may provide constraints on GRB models based on our prediction.

2. GRB Flux Models

Buried jet model:– Massive stars undergoing a sudden core-collapse which may form a black hole are thought to be the progenitors of long duration GRBs. Matter falling into the black hole can give rise to an ultra-relativistic jet. The jet burrows through the stellar material, and may or may not break through the stellar envelope.[6] Internal shocks in the jet, while it is burrowing through the stellar interior, may produce high energy ν's through pp and $p\gamma$ interactions.[7] The jets which successfully penetrate through the stellar envelope result in GRBs (γ-ray bright) and the jets which choke inside the stars do not produce GRBs (γ-ray dark). However, in both cases high energy ν's are emitted through the stellar envelope since they interact very weakly with matter. High energy ν's from the buried jets are emitted as precursors to the ν's emitted from the GRB fireball. Neutrino signal from two progenitor star models of radii $10^{12.5}$ cm (H) and 10^{11} cm (He) are plotted in Fig. 1.

Supranova model:– Observations of a number of GRBs followed by SNe may be modeled in a two step collapse scenario of massive stars. A SN explosion takes place first leaving an expanding SN remnant (SNR) shell and the GRB takes place days later. Initially the SNR shell is optically thick and the photons are trapped inside. SN signature shows up in the light curves days after the GRB when the SNR shell becomes optically thin. However, simultaneous GRB and SN scenario is also consistent with observations. Photons cannot resolve the time delay between the events to less than a few days but high energy ν's can since the SNR shell is transparent to ν's. If the SN explosion takes place before the GRB, high energy ν's are produced by pp and $p\gamma$ interactions of shock accelerated protons which escape the GRB fireball with photons and baryons trapped inside the SNR shell.[2] These ν's are contemporaneous with ν's emitted from the GRB fireball itself (see Fig. 1).

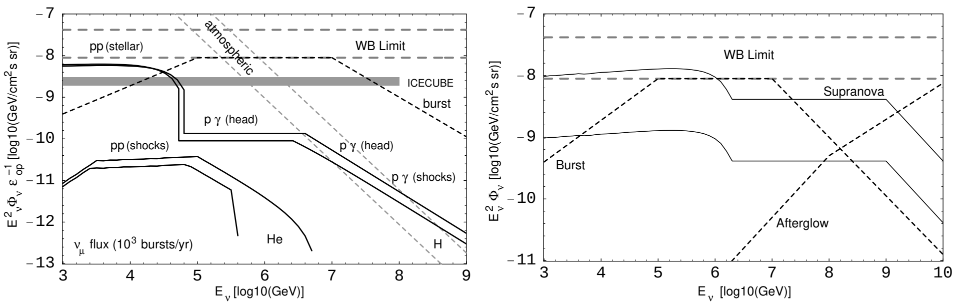

Fig. 1. *Left panel:* Diffuse ν_μ flux (solid lines) from sub-stellar jet shocks in two GRB progenitor models (H and He). These neutrinos arrive 10-100 s before the γ-ray bright bursts. Also shown is the diffuse ν_μ flux (burst) arriving simultaneously with the γ-rays from shocks outside the stellar surface in observed GRBs; the Waxman-Bahcall (WB) diffuse cosmic ray bound; and the atmospheric neutrino flux. For a hypothetical 100:1 ratio of γ-ray dark to γ-ray bright collapses, the ν_μ spectral curves would be 100 times higher. *Right panel:* Diffuse ν_μ flux from post-supernova (supranova) models of GRBs, assuming that (top curve) all GRBs have an SNR shell, or (bottom) 10% of all GRBs have an SNR shell, and 10^{-1} of the fireball protons reach the shells.

3. Detection Prospect

Most GRBs are located at cosmological distance (redshift $z \sim 1$) and individual detection of them by km scale neutrino telescopes is unlikely. The diffuse ν flux is then dominated by a few nearby bursts. The likeliest prospect for UHE ν detection is from these nearby GRBs in correlation with electromagnetic detection.

We have calculated expected ν_μ and ν_e events (see Table 1) from such a nearby burst ($z \approx 0.17$) which took place on March 29, 2003 (GRB 030329), associated with SN 2003dh, in a km^2 ice Cherenkov detector (e.g. IceCube) at the South pole.[8] We used different flux models as discussed before and the full detection probability, depending on the source's angular position, for our calculation.

Table 1. Expected neutrino events for different flux components from a GRB similar to GRB 030329 in a km scale detector. Also listed (within parentheses) are expected numbers if a similar event takes place at 180° (↑) and 90° (→) angles with respect to the zenith angle.

Component	TeV-PeV ν_μ	TeV-PeV ν_e	PeV-EeV ν_μ	PeV-EeV ν_e
Precursor I	$9 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	-	-
	$(6 \cdot 10^{-3} \uparrow 0.01 \rightarrow)$	$(2 \cdot 10^{-3} \uparrow 2 \cdot 10^{-3} \rightarrow)$	-	-
Precursor II	4.1	1.1	$3 \cdot 10^{-3}$	$2 \cdot 10^{-4}$
	$(2.9 \uparrow 4.4 \rightarrow)$	$(0.9 \uparrow 1.2 \rightarrow)$	$(0.01 \rightarrow)$	$(8 \cdot 10^{-4} \rightarrow)$
Burst	1.8	0.2	1.4	0.1
	$(0.3 \uparrow 2.9 \rightarrow)$	$(0.04 \uparrow 0.3 \rightarrow)$	$(7.6 \rightarrow)$	$(0.4 \rightarrow)$
Afterglow	$2 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-4}$	$1 \cdot 10^{-5}$
(ISM)	$(3 \cdot 10^{-5} \uparrow 2 \cdot 10^{-4} \rightarrow)$	$(4 \cdot 10^{-6} \uparrow 2 \cdot 10^{-5} \rightarrow)$	$(0.01 \rightarrow)$	$(5 \cdot 10^{-4} \rightarrow)$
Afterglow	0.03	$3 \cdot 10^{-3}$	0.05	$3 \cdot 10^{-3}$
(wind)	$(5 \cdot 10^{-3} \uparrow 0.05 \rightarrow)$	$(7 \cdot 10^{-4} \uparrow 5 \cdot 10^{-3} \rightarrow)$	$(1.4 \rightarrow)$	$(0.06 \rightarrow)$
Supranova	12.4	2.4	0.5	0.03
0.1 d	$(6.1 \uparrow 14.9 \rightarrow)$	$(1.6 \uparrow 2.7 \rightarrow)$	$(1.6 \rightarrow$	$0.1 \rightarrow)$
Supranova	12.4	2.4	0.5	0.03
1 d	$6.1 (\uparrow 14.9 \rightarrow)$	$(1.6 \uparrow 2.7 \rightarrow)$	$(1.9 \rightarrow)$	$(0.1 \rightarrow)$
Supranova	10.9	2.2	0.4	0.03
8 d	$(5.4 \uparrow 13.2 \rightarrow)$	$(1.4 \uparrow 2.4 \rightarrow)$	$(1.7 \rightarrow)$	$(0.1 \rightarrow)$

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