Starlight beneath the waves : in search of TeV photon emission from Gamma-Ray Bursts with the ANTARES Neutrino Telescope

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Part IV

Epilogue

12 Conclusions and outlook

THE AUTHOR is of the opinion that the attempt to detect very-high energy (VHE) γ-rays from GRBs is a most difficult venture. Some of these difficulties will be discussed in the following.

It is possible that VHE γ-rays are not always produced in a GRB, as the production of VHE γ-rays in GRBs is determined largely by the bulk Lorentz factor Γ. As discussed in Chapter 2, the compactness of the GRB fireball is highly-dependent on Γ and will introduce a cutoff in the emitted γ-ray spectrum. The high-energy cutoff $\epsilon_{\rm cut}$ of the energy spectrum is approximated by Asano & Inoue (2007) as

$$\epsilon_{\rm cut} \simeq \Gamma_{100}^4 L_{\rm iso,51}^{-1/2} \left(\frac{\delta t}{1\ \rm s}\right)^{1.3}\ \rm GeV, \tag{12.1}$$

where $\Gamma_{100} = 10^{-2}\Gamma$ is the Lorentz factor of the GRB fireball, $L_{\rm iso,51} = L_{\rm iso}/(10^{51}\ \rm erg\ s^{-1})$ is the isotropic luminosity of the GRB, and δt is the time variability of the GRB in the source frame. From this Equation we can see that Γ must be $\sim$1000 to allow for γ-rays of energies $\epsilon_\gamma \lesssim 10$ TeV to escape from the fireball, assuming a variability timescale $\delta t = 1$ s. This value of Γ is well above that constrained by Lithwick & Sari (2001), which is generally between 100 and 400. While GRB 090510 has been observed to have $\Gamma \gtrsim 1200$ (Ackermann et al., 2010), this GRB might represent the higher end of a wide distribution in the bulk Lorentz factor Γ, and a typical GRB will have $\Gamma \sim 200$–720 (Ackermann et al., 2012).

Even if VHE γ-rays can escape the fireball, they will interact with the cosmic infrared background radiation. The γ-rays are annihilated, producing electron–positron pairs in its place. The optical depth $\tau_{\gamma\gamma}$ is a function of γ-ray energy and of the distance to the GRB. As we have seen in Section 2.3, the attenuation limits our observation only to the nearest GRBs. As can be seen from Figure 2.3, the cutoff in the observed photon spectrum is already severe for redshift $z \sim 0.2$. This effectively limits our observation only to the nearest GRB with redshift $z \lesssim 0.2$, which according to Le & Dermer (2007) has only a probability of $P(z \leq 0.2) \sim 6.5 \times 10^{-3}$ of occuring. Despite this low probability predicted by theoretical analyses, in the last 14 years alone we have observed at least 6 GRBs with $z \leq 0.1$ and 12 GRBs with $z \leq 0.2$. This means that nearby GRBs could occur with higher frequency than what was predicted by theory.

The depth of the detector provides excellent shielding against muon background events. However, if the detector is too deep then even muon signal events can not penetrate to that depth. Consequently, the neutrino telescope can not play its role as a γ-ray observatory. The depth of the ANTARES neutrino telescope already provides sufficient shielding while still allowing energetic muons to reach the detector. To operate an underwater neutrino telescope as a γ-ray telescope, it is better if the detector is not deployed to a depth of more than $\sim$2500 m.

From the analysis of the expected muon rate from a single GRB event, we found out that the muon rate is largely dependent on three quantities: The distance to the GRB, the hardness of the GRB energy spectrum, and the size of the detector. The distance of the GRB, represented by its redshift z, determines the number of γ-rays that survive to reach Earth. The hardness of the energy spectrum, represented by its high-energy spectral index β, determines the growth or dissipation of the electromagnetic shower in the atmosphere. Finally, the size of the detector determines the number of detectable muons. An ANTARES-sized telescope however requires a typical GRB with spectral index $\beta = -2$ to be at a redshift $z \lesssim 0.05$. This puts a heavy constraint on the discovery potential as a GRB event that occurs at so small a redshift is very rare. A km^3-sized neutrino telescope will have a horizon up to $z \lesssim 0.1$.

It is also possible to observe all detected GRBs that occur above the local horizon of the detector and stack them as if they are one single source. In order to understand this method, GRB events are simulated using distribution functions that reflect the properties of a GRB. From this simulation we learned that the effective area of the detector must be at least of the order of $A_{\mu}^{\text{eff}} = 1$ km^2 to obtain at least 50% probability of making a discovery with 3σ significance or better in 5 years.

Simulations of the ANTARES Neutrino Telescope's response to downgoing muons show that the detector is capable of reconstructing downgoing muon tracks with reasonable efficiency. The muon detection efficiency is approximately ∼20% at a muon energy $\epsilon_\mu = 10$ TeV. This corresponds to a muon effective area of approximately $A_\mu^{\rm eff} \sim 0.05$ km^2. This relatively small size decreases the redshift threshold even further. GRBs must then occur at redshift $z \lesssim 0.01$ in order to be detected by ANTARES.

It is to be understood that ANTARES is built more as a proof of principle for an undersea neutrino telescope—a continuation of the legacy left by its predecessors such as DUMAND and the still-active Baikal—than as an instrument of discovery. What has been shown in this dissertation is that the detector is capable to detect downgoing muon events with relatively good accuracy and that a physics analysis can be applied to these data. We have also seen that a statistical analysis can be applied to the data in order to impose a limit on the TeV flux of a selected GRB target.

The sensitivity plot shown in Figure 11.12 implies that the 90% confidence level of ANTARES sensitivity at 10 TeV is

$$\nu f_{\nu,90}(10\ \text{TeV}) = 4 \times 10^{-4}\ \text{erg cm}^{-2}\ \text{s}^{-1}. \tag{12.2}$$

This result shows that ANTARES is much less sensitive than other ground-based γ-ray observatories such as *Milagro*, MAGIC, or HESS. *Milagro* observed 28 GRBs between 2000–2008 and the best upper limit they obtained at 99% confidence level is $\nu f_{\nu,99}(> 100\ \text{GeV}) \sim 10^{-6}$ erg cm^{-2} s^{-1} (Aune, 2009). Between 2005–2006, the MAGIC telescope observed 9 GRBs during their afterglow phase and obtained average upper limits in the order of $\langle \nu f_\nu \rangle \sim 10^{-8}$ erg cm^{-2} s^{-1} (Albert et al., 2007). HESS observed GRB 060602B during its prompt and afterglow phases, and obtain an upper limit for $\epsilon_\gamma > 1$ TeV at 99% confidence level of $\nu f_{\nu,99}(> 1\ \text{TeV}) = 2.9 \times 10^{-9}$ erg cm^{-2} s^{-1} (Aharonian et al., 2009). Even though MAGIC and HESS have better sensitivities than *Milagro*, their low duty cycle and slow slew rate make it dificult for them to observe GRBs in the prompt phase.

The currently largest neutrino telescope in the world, IceCube, might be able to play a role as a γ-ray observatory. Two southern GRBs were recently detected by *Swift* and should be within the field of view of IceCube (Table 12.1). The host galaxy of GRB 100316D was identified to be at redshift $z = 0.059$ (Vergani et al.,

Name	T_0 [UT]	α_{J2000} [h:m:s]	δ_{J2000} [° ′ ″]	T_{90} [s]	z	References
100316D	12:44:50	$07^h10^m30.63^s$	$-56°15'19.7''$	240	0.059	Vergani et al. (2010)
111005A	08:05:14	$14^h53^m15.6^s$	$-19°43'19.1''$	26	0.01326?	Levan et al. (2011)

Table 12.1: The parameters of two nearby southern GRBs whose TeV γ-ray emission could possibly be observed by IceCube.

2010) and an associated supernova, SN 2010bh was detected by Wiersema et al. (2010). The host of GRB 111005A was not identified as the GRB occured at ∼35° from the Sun. However, Levan et al. (2011) noticed that the BAT error circle contains a bright, nearby galaxy at redshift $z = 0.01326$. If GRB 111005A is indeed associated with this galaxy, then it would be the closest GRB identified since GRB 980425/SN 1998bw. Observing these two GRBs with IceCube could provide us with interesting results given the capabilities of IceCube.

Future neutrino telescopes such as the Gigaton Volume Detector (GVD) in Lake Baikal and KM3NeT in the Mediterranean Sea will have a more serious chance to impose a stricter limit or making a discovery. As mentioned in Chapter 1, KM3NeT is expected to be completed in 2020 and is expected to cover an instrumented volume of 5–8 km^3. The site for KM3NeT has not yet been determined at this time, however the design for the spherical casing that will house the PMTs has been defined.

Figure 12.1: The prototype of the KM3NeT digital optical module (DOM). Credit: Propriety KM3NeT Consortium, `http://km3net.org`

The digital optical module (DOM) of KM3NeT (Figure 12.1) will be a 17-inch glass sphere equipped with 31 3-inch PMTs. The PMTs are oriented towards various directions, from straight down to about 45° upwards. The advantages of this design among others are that the overall photocathode area exceeds that of a 10-inch PMTs by more than a factor of three, and that it provides more directional sensitivity (Katz & Spiering, 2012). With this design and its large volume, the sensitivity of KM3NeT to VHE γ-rays could be increased to as much as a factor of 15 as compared to ANTARES. Combine this large volume with a reconstruction algorithm that can accurately reconstruct the direction of muons of lower energies and better background rejection method, the sensitivity of KM3NeT could be increased to as much as 100 times that of ANTARES.

HAWC might be the detector with the best chance to observe TeV γ-rays from GRBs. It has not only a wide field-of-view with near 100% duty cycle, but also a large photon collecting area with $A_{\gamma}^{\mathrm{eff}} \sim 10^5$ m^2 at $\epsilon_{\gamma} = 10$ TeV (Abeysekara et al., 2012). HAWC is expected to have a sensitivity of $\nu f_{\nu} \sim 10^{-7}$ erg cm^{-2} s^{-1} for GRBs at a zenith distance of approximately 30° (Abeysekara et al., 2012). This is still ∼10 times less sensitive than MAGIC and ∼100 times less than HESS, but the clear advantages of HAWC over both instruments are its aforementioned field-of-view and duty cycle.

The first confirmed discovery of TeV γ-rays from GRBs might be performed by HAWC several years after it is completed in 2014, however as we have seen in Chapter 5 it is possible that a detection of at least 3σ significance could be achieved by KM3NeT within 5 years after it has been completed.