Milagro–A TeV Observatory for Gamma Ray Bursts

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Abstract. Milagro is a large field of view ($\sim$ 2 sr), high duty cycle ($\sim$90%), ground-based observatory sensitive to gamma-rays above $\sim$100 GeV. This unique detector is ideal for observing the highest energy gamma-rays from gamma-ray bursts. The highest energy gamma rays supply very strong constraints on the nature of gamma-ray burst sources as well as fundamental physics. Because the highest energy gamma-rays are attenuated by pair production with the extragalactic infrared background light, Milagro's sensitivity decreases rapidly for bursts with redshift $>$ 0.5. While only 10 % of bursts have been measured to be within z=0.5, these bursts are very well studied at all wavelengths resulting in the most complete understanding of GRB phenomena. Milagro has sufficient sensitivity in units of E^2 dN/dE to detect VHE luminosities lower than the observed luminosities at $\sim$ 100 keV for these nearby bursts. Therefore, the launch of SWIFT and its ability to localize and measure redshifts of many bursts points to great future possibilities.

IMPORTANCE OF HIGH ENERGY OBSERVATIONS

The observations of very high energy (VHE), $>\sim$ 100 GeV, flux from GRBs are few. At slightly lower energies, EGRET observed GRBs emission up to $\sim$ 20 GeV [1] and no cutoff up to 10 GeV in the average prompt spectrum of differential spectral index -1.95 $\pm$ 0.25 [2]. Recently a GRB has been reported with an even brighter (at least 3 times the fluence) higher energy component that begins at a few MeV and extends to at least 200 MeV with a differential spectral index of -1.0 $\pm$ 0.3 [3]. Milagrito, a small prototype of Milagro, observed an excess from the GRB on 17 April 1997 which implied more VHE fluence than the MeV fluence detected by BATSE [4], but the significance of the detection was marginal ($\sim 3\ \sigma$). Also, air Cherenkov telescopes have attempted to look for VHE afterglow emission, but have not detected any (e.g. [5]).

However, VHE gamma rays are a natural byproduct of most GRB production models and are often predicted to have comparable fluence at TeV and MeV scales (e.g. [6], [7], [8]). This is due to the fact that the MeV emission from GRBs is likely due to synchrotron radiation produced by highly accelerated electrons within the strong magnetic field of a jet with bulk Lorentz factors exceeding 100. In such an environment, the inverse Compton mechanism for transferring energy from electrons to gamma rays is likely to complement synchrotron radiation and produce a second VHE component of GRB emission with fluence possibly peaked at 1 TeV or beyond. Whether or not the inverse Compton mechanism contributes minimally or even dominates the energy production depends on the environment of the particle acceleration and the gamma-ray production. VHE measurements may be critical to the understanding of gamma-ray production in GRBs similar to the manner in the TeV measurements have resolved the degeneracy between magnetic field and electron energy in blazars. In addition, GRBs will likely accelerate hadrons-maybe even producing the ultra high energy cosmic rays [9], [10]. Hadrons will create TeV gamma rays via cascades made by photo-pion production or possibly through synchrotron emission of protons [11].

VHE emission from GRBs is attenuated by interactions with the extragalactic infrared background light producing electron-positron pairs. The amount of absorption is uncertain because the infrared photon density cannot be directly measured due to the foreground of our own galaxy. Several models exist for the infrared light which is due to reprocessed starlight and therefore depends on stellar and galaxy evolution at earlier epochs. Unfortunately, this reduces the sensitivity of VHE observatories especially at higher energies. Fortunately, VHE detections and spectra also constrain the infrared photon density. Thus, VHE observations at different redshifts contribute to our fundamental understanding of the evolution of the Universe.

Fundamental physics can also be probed by the detection of VHE emission from a GRB, by providing the most sensitive measurement to date for the constancy of the speed of light as a function of energy. Some quantum gravity theories predict a breakdown of Lorentz invariance observable as an energy dependency of the speed of light, which can be written as $v = c(1 - \xi E_\gamma / E_{QG})$ [12], where ξ is of order 1 and E_{QG} is the energy scale at which quantum gravity becomes important. Based on this formula the following figure of merit may be derived – $Q = 4x10^{17} z E_{GeV} / \Delta t_{sec}$, where z is the redshift to the source, E_{GeV} is the energy of the photons detected in GeV, and Δt_{sec} is the duration of the event in seconds. The best limit on E_{QG} ($> 6x10^{16}$ GeV) was derived from a 30 minute flare from the active galaxy Mrk 421 detected in the TeV energy band by the Whipple air Cherenkov telescope [13]. A 1-second gamma-ray burst at a redshift of 0.3, detected above 300 GeV would be sensitive to effects where E_{QG} is above 10^{19} GeV, the Planck scale. Thus if a satellite-based gamma-ray observatory can measure both the redshift and lightcurve of the burst, a VHE detection would probe the nature of spacetime at energies near or beyond the Planck scale.

MILAGRO’S CAPABILITIES

Milagro is a new type of ground-based gamma-ray observatory which detects the particles in the extensive air showers created when a VHE gamma ray interacts with the Earth’s atmosphere. This technique has been proven successful with Milagro’s detection and VHE flux measurement of the Crab nebula [14] and Mrk 421 [15]. Milagro is located in the Jemez mountains near Los Alamos, New Mexico and has been operational since January 2000. Recently the detector has been upgraded to improve the angular resolution, the energy resolution, the cosmic-ray background rejection efficiency, and to lower the energy threshold. Individual showers are reconstructed with an average angular resolution of 0.5^o, which depends on the number of the particles in the shower and the primary energy of the gamma ray.

Milagro is ideally suited to observe VHE emission from GRBs. The alternative technique of detecting VHE gamma rays from the Cherenkov light created in the atmosphere by the particles in the extensive air show is more sensitive, but less well suited to observations of GRBs due to the small field of view of a few square degrees and the low duty cycle of 5-10%. In contrast, Milagro's average uptime was $> 90\%$ for the last year, and the field of view is ~ 2 sr. Milagro's effective area is ~ 10 m^2 at 100 GeV increasing to greater than 10^4 m^2 at a few TeV. The background rate of cosmic-rays is $\sim 1700/$sec within this 2 sr field of view, but only $\sim 3/$sec are consistent with any individual point source.

Using the known background rate and the Monte Carlo simulated effective area (which was confirmed by the determination of the known Crab flux), Milagro's sensitivity to a 100 second duration gamma-ray burst is quantified in Figure 1 as a function of the GRB redshift. The extragalactic, infrared background light model of [16] is used to attenuate the observed spectrum at different redshifts. The plotted lines are for different zenith angle ranges and give the minimum required luminosity in units of E^2 dN/dE emitted at the source at 100 GeV assuming a differential photon spectrum of E^{-2}. The field of view decreases slightly at higher redshifts because the energy threshold of Milagro increases as the effective depth of the atmosphere increases at larger zenith angles.

The VHE luminosity of GRBs in unknown, but if the VHE luminosity is comparable to the luminosity emitted at $\sim$ 100 keV (shown as triangles in Figure 1) and if GRB luminosity is not strongly correlated with redshift, then Milagro has excellent sensitivity to GRBs with $z < 0.5$ and some sensitivity to $z \sim 1$. Over 10% of GRBs with measured redshifts are nearer than $z = 0.5$, and given Milagro's field of view is one sixth of the sky, Milagro's sensitivity in units of E^2 dN/dE is lower the detected isotropic luminosities for a few percent of the GRB detected.

Milagro has searched for VHE emission from GRBs detected by satellites; however, fewer than 40 bursts have been localized to be within Milagro's field of view during its operation from January 2000 until present. This number 40 can be compared with the 54 bursts searched for VHE emission with the Milagrito VHE gamma-ray detector, of which one candidate was found, GRB970417a [4]. None of these bursts have been detected by Milagro, but one of the bursts was especially interesting due to its nearby redshift. An upper limit was derived from the Milagro data for this GRB at a redshift of 0.45 on 21 September 2001 assuming the infrared extragalactic background absorbs all gamma-rays above 150 GeV [17]. Milagro's upper limit for this burst is below the extrapolation of the spectrum measured by HETE, and this upper limit was announced promptly via a GCN Circular.

The Milagro data itself is also being searched online for transients of duration 250 microseconds up to 2 hours. The results of the search are emailed within a few seconds to Milagro collaboration members for verification. No significant transient sources have been detected and the nondetection has been used to place an upper limit on the number of TeV emitting GRBs which depends on the redshift distribution of GRBs [18] [19].

Milagro will continue operation during the SWIFT mission. Milagro's continuous operation and large field of view guarantees approximately one sixth of GRBs will be observed before, during, and after the SWIFT detection. Milagro will use the GCN to disseminate VHE detection information such as photon flux and duration. We will also directly notify other interested observers–for example, TeV air Cherenkov telescopes,

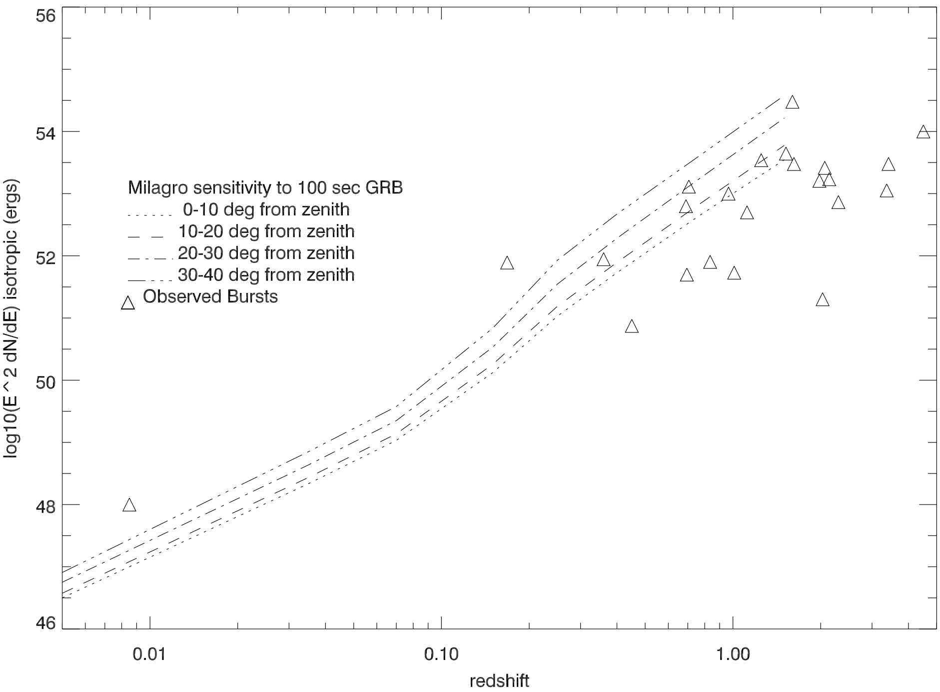

FIGURE 1. Isotropic luminosity required for a 5 σ detection by Milagro for a 100 sec duration gamma-ray burst at different redshifts. The differential photon GRB spectrum is assumed to be E^{-2} and is attenuated by extragalactic, infrared, background light as predicted in [16]. Triangles indicate the isotropic luminosity of GRBs observed at $\sim$100 keV.

which have sensitivities (in E^2 dN/dE units) comparable to past X-ray afterglow detections. For nondetections of VHE emission, we will update a web page listing all SWIFT GRBs observed giving flux upper limits for different durations. Also, we will continue searching our own data for any evidence of a VHE-detected GRB, and will promptly notifying the community of any positive detections.

CONCLUSION

Milagro is a new type of large field of view, VHE gamma-ray detector that has been proven to work with the detection of astrophysical sources. This new technique is essential to detect VHE gamma rays from gamma-ray bursts, and Milagro has sufficient sensitivity to test theoretical predictions of GRB emission, as well as the possibility to make fundamental observations. We eagerly await the launch of SWIFT, and the many localizations of GRBs to follow.

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