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# MUON DETECTION OF TeV GAMMA RAYS FROM GAMMA-RAY BURSTS

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## ABSTRACT

Because of the limited size of the satellite-borne instruments, it has not been possible to observe the flux of gamma-ray bursts (GRBs) beyond GeV energy. We here show that it is possible to detect the GRB radiation of TeV energy and above by detecting the muon secondaries produced when the gamma rays shower in Earth's atmosphere. Observation is made possible by the recent commissioning of underground detectors (AMANDA, the Lake Baikal detector, and MILAGRO), which combine a low muon threshold of a few hundred GeV or less, with a large effective area of $10^3$ $m^2$ or more. Observations will not only provide new insights in the origin and characteristics of GRB, but they also will provide quantitative information on the diffuse infrared background.

*Subject headings:* cosmic rays — gamma rays: bursts — nuclear reactions, nucleosynthesis, abundances

## 1. MUON BURST ASTRONOMY

High-energy gamma rays produce muons when interacting in Earth's atmosphere. These can be efficiently detected, and the direction of the parent gamma ray reconstructed, in relatively shallow underground "neutrino" detectors (Gaisser, Halzen, & Stanev 1995 and references therein) such as the now operating Antarctic Muon and Neutrino Detector Array (AMANDA) (AMANDA 1998) and Lake Baikal telescope (BAIKAL 1998; Sokalski & Spiering 1992; Spiering 1998). These instruments are positioned at a modest depth of order 1 km and are therefore sensitive to muons with energies of a few hundred GeV, well below the TeV thresholds of other deep underground detectors such as Superkamiokande and MACRO (Gaisser et al. 1995). They are therefore able to detect muons from primary gamma rays of TeV energy and above, with a very large effective telescope area of $10^3$ $m^2$, or more. They infer the photon direction by reconstructing the secondary muon track with degree accuracy. Although muons produced by gamma rays from astronomical sources compete with a large background of atmospheric cosmic-ray–induced muons, during the short duration of a GRB, this background is manageable. Using the time stamp provided by satellite observation, the detector integrates background only over the very short time of the burst, which is of order 1 s. Unlike air Cherenkov telescopes, muon detectors cover a large fraction of the sky with a large duty cycle, e.g., essentially 100% efficiency for more than one-quarter of the sky in the case of the AMANDA detector with a South Pole location.

In this paper we demonstrate how large-area detectors operating with a few hundred GeV muon threshold, or less, provide a unique window of opportunity for observing GRBs. While the fluxes of TeV photons are reduced by 1 or more orders of magnitude compared to GeV photons observed with satellites, and while only 1% of the gamma rays will produce a detected secondary muon, observation of GRBs is possible because the detectors are 4 orders of magnitude larger than, for example, the EGRET instrument on the *Compton Gamma Ray Observatory* (Thompson et al. 1995).

By the most conservative estimates, we predict order 1 muon per year correlated in time and direction with GRBs for the operating detectors and as high as 50 per year for the most conservative GRB flux estimate normalized to the observed diffuse GeV cosmic background (Vázquez 1998; Totani 1999). The unknown energetics of GRBs above GeV may yield much higher rates; see, for instance, Totani (1998). Interestingly, the muon count is similar for a single nearby burst at redshift $z = 0.1$, and a flux of a few muons or more in a 1 s interval in coincidence with a gamma-ray burst cannot be missed. For a cosmological distribution, such an event occurs within 2–3 yr of observation, taking into account all observational constraints.

Failure to observe a signal within a few years would establish a cutoff on the GRB flux not much above the GeV sensitivity of the operating detectors or would point to an unexpectedly large infrared diffuse background absorbing the TeV gamma rays over cosmological distances. The two possibilities can be distinguished on the basis of observation of the occasional nearby burst. There is also the possibility of cosmological evolution of the sources. The observations are obviously relevant to the proposal that GRBs are the sources of the highest energy cosmic rays (Vietri 1998 and references therein; Waxman 1995).

Also of interest here is the MILAGRO detector (Yodh 1995[1]) and the proposed HANUL experiment in Korea (Lee 1998). Although of more modest size compared to "neutrino" telescopes, MILAGRO's muon threshold is only 1.5 GeV because of its location at the surface. Sensitivity to gamma rays of lower energy results in an increased flux and compensates for its smaller effective area. We should here point out that MILAGRO, as well as the other instruments discussed, have other capabilities to study GRBs. For instance, AMANDA has sensitivity to the MeV neutrinos produced in the initial collapse (Halzen & Jaczko 1996) and to neutrinos of TeV energy and above (AMANDA 1998). The MILAGRO detector, beyond counting muons, can efficiently reconstruct gamma-ray

[1] See also the MILAGRO home page, http://umauhe.umd.edu/milagro.html.

showers once their energy exceeds hundreds of GeV (Yodh 1995).

That the MILAGRO experiment can detect GRBs with this method has been pointed out in Halzen, Stanev, & Yodh (1997). The rate calculation will, however, be sharpened here. Halzen et al. constructed a generic differential flux and treated the duration of the burst as a parameter. Obviously, the total fluency specifies the duration and makes a specific prediction. We will here predict GRB muon burst rates in MILAGRO that are definite and consistent with Halzen et al. (1997) if one fixes the correct value of the duration by total energy considerations. The relevance of other neutrino experiments to the detection of TeV photons from GRB was not anticipated.

## 2. MUONS IN GAMMA-RAY SHOWERS

When gamma rays interact with the atmosphere, they initiate cascades of electrons and photons but also some muons. The dominant source of muons is the decay of charged pions that are photoproduced by shower photons. The number of muons with energy above $E_\mu$ in a shower initiated by a photon of energy $E_\gamma$ was computed some time ago (Halzen, Hikasa, & Stanev 1986 and references therein). For $E_\mu$ in the range 0.1–1 TeV the number of muons in a photon shower can be parameterized as

$$N_\mu(E_\gamma, > E_\mu) \simeq \frac{2.14 \times 10^{-5}}{\cos\theta} \frac{1}{(E_\mu/\cos\theta)} \left[\frac{E_\gamma}{(E_\mu/\cos\theta)}\right], \quad (1)$$

with energy in TeV units. The parameterization is valid for $E_\gamma/E_\mu \geq 10$. This parameterization is adequate to calculate muon rates in the AMANDA and Baikal detectors since both have muon thresholds of the order of a few hundred GeV.

For muons energies below 0.1 TeV, muon decay and muon energy losses in the atmosphere must be taken into account. To accomplish this we have used a linear shower Monte Carlo simulation that follows all shower particles down to muon threshold. It accounts for all decay modes and energy losses (Gaisser 1990). We have calculated the number of muons at sea level with energy above 1.5 GeV, which is MILAGRO's threshold for muon detection. We have parameterized the results as a function of initial photon energy at different zenith angles for use in subsequent calculations.

The Monte Carlo simulation calculates the production of muons by the decay of photoproduced pions. The photoproduction cross section is obtained by interpolation of $\gamma$-proton data, including the most recent high-energy measurements (Caso et al. 1998) performed with accelerators. It is converted to a $\gamma$-air cross section using the empirical $A^{0.91}$ dependence on the atomic number. A constant diffractive cross section of 0.194 mb proceeding via $\rho$ production has been included in the Monte Carlo simulation. For high-energy muons, the Monte Carlo results are adequately parameterized by equation (1).

We here neglected the production of muons by direct $\mu$-pair production and leptonic decay of charmed particles, which contribute to the flux of muons with energy only above several TeV (Halzen et al. 1986).

## 3. GRB MUON RATES FROM ENERGY CONSIDERATIONS

It is thought that GRBs are produced when a highly relativistic shock with Lorentz factor of order 100 or higher dissipates its kinetic energy in collisions with the interstellar medium or in internal collisions within the relativistic ejecta. The observed gamma rays are most likely produced by synchrotron radiation of electrons accelerated in the shock, possibly followed by inverse Compton scattering, when the relativistic shell becomes optically thin to pair production (for a recent review on GRBs, see Piran 1998 and references therein).

The observed injection rate in the universe is $\dot{E}_{\rm GRB} = 4 \times 10^{44}$ ergs Mpc$^{-3}$ yr$^{-1}$. Interestingly, this is equal to the injection in cosmic rays beyond the ankle in the spectrum near $10^6$ TeV (Vietri 1998; Waxman 1995). The BATSE instrument observes, on average, 1 GRB per day with an efficiency of about 25%. Therefore the average energy emitted per burst, $E_{\rm GRB}$, is

$$E_{\rm GRB} \simeq 3 \times 10^{52}\ {\rm ergs}\left(\frac{D}{3000\ {\rm Mpc}}\right)^3 \times \left(\frac{\dot{E}}{4 \times 10^{44}\ {\rm ergs\ Mpc^{-3}\ yr^{-1}}}\right)\left(\frac{4\ {\rm day}^{-1}}{R}\right), \quad (2)$$

where $R$ is the burst rate. Throughout our analysis we will assume a cosmological distribution of GRBs, with a distance of $D = 3000$ Mpc to the average burst. Assuming no beaming, this energy corresponds to an average fluency per GRB, $F_{\rm GRB}$, close to the one observed:

$$F_{\rm GRB} = 3 \times 10^{-8}\ {\rm J\ m^{-2}}\left(\frac{3000\ {\rm Mpc}}{D}\right)^2\left(\frac{E_{\rm GRB}}{3 \times 10^{52}\ {\rm ergs}}\right). \quad (3)$$

Although in line with observations, this may be an underestimate because present detectors provide no information on the energetics of GRBs above GeV energy. Some authors (Vázquez 1998; Totani 1998) have, for instance, raised the interesting possibility that GRBs are the origin of the diffuse extragalactic gamma-ray background. This association requires a photon energy of order $E_{\rm GRB} \sim 10^{54}$–$10^{56}$ ergs per burst, depending on the GRB occurrence rate assumed. Most of this energy is concentrated in the high-energy tail of the photon spectrum, above $E_\gamma > 1$ TeV, and is therefore not included in the energy balance of equation (2), where only observed photons of GeV energy and below have been considered. There are models that can accommodate the large total energy required by this scenario; for instance, those in which a complete neutron star is converted into photons (Pen, Loeb, & Turok 1998).

A typical GRB spectrum exhibits a high-energy tail that, above a few hundred keV, can be parameterized by a power law:

$$\frac{dN_\gamma}{dE_\gamma} = \frac{F_\gamma}{E^{(\gamma+1)}}\ 10^{-12}\ {\rm cm^{-2}\ s^{-1}}, \quad (4)$$

where energies are in TeV. Typical values for the observed spectral index $\gamma$ range from 0.8 to 1 (Piran 1998). The photon spectrum of the average burst is normalized by energy conservation:

$$\int_{E_{\gamma\rm min}}^{E_{\gamma\rm max}} dE_\gamma\, E_\gamma \frac{dN_\gamma}{dE_\gamma} = \frac{F_{\rm GRB}}{\Delta t}, \quad (5)$$

where $\Delta t$ is the average duration of the burst of order 1 s. $E_{\gamma\rm min}$ ($E_{\gamma\rm max}$) is the minimum (maximum) energy of the photons emitted by the burst. For $E_{\gamma\rm min}$, we will use 1 MeV throughout. Observations indicate indeed that a negligible fraction of the energy is emitted in X-rays.

The TeV flux obtained by extrapolation is too low to be detected by the present satellite experiments because of their small telescope area. The high-energy behavior of the GRB spectrum is therefore a matter of intense speculation. Bursts in which isolated photons reach tens of GeV energy have been detected, which suggests the extension of the spectrum to the TeV range (Piran 1998). As previously discussed, the extension of the photon spectrum to TeV energy with a rather flat spectral index ($\gamma \sim 0.5$) is an essential feature of models accommodating the diffuse GeV background. Also, the HEGRA group (Padilla et al. 1998) has observed an excess of gamma rays with $E_\gamma > 16$ TeV in temporal and directional coincidence with GRB 920925c.

The value of $F_\gamma$ obtained through above normalization procedure is given by

$$F_\gamma = 3 \times 10^4 \left(\frac{3000 \text{ Mpc}}{D}\right)^2 \left(\frac{E_{\rm GRB}}{3 \times 10^{52} \text{ ergs}}\right) \times \begin{cases} (1-\gamma)[E_{\gamma\max}^{(1-\gamma)} - E_{\gamma\min}^{(1-\gamma)}]^{-1} & \text{for } \gamma \neq 1 \\ \left[\ln\left(\frac{E_{\gamma\max}}{E_{\gamma\min}}\right)\right]^{-1} & \text{for } \gamma = 1 . \end{cases} \quad (6)$$

Note that, to a first approximation, the normalization factor $F_\gamma$ depends only on $E_{\gamma\min}$ ($E_{\gamma\max}$) for $\gamma > 1$ ($\gamma < 1$). The reason for this is clear; when $\gamma > 1$, the spectrum is very steep, and most of the GRB energy is concentrated in lower energy photons. The situation is reversed in the case of $\gamma < 1$. We will explore the dependence of the muon rate on $\gamma$ further on.

Absorption of gamma rays in the infrared, optical, and microwave backgrounds is a determining factor in the gamma ray flux observed at Earth. The mean free path of a TeV photon in the diffuse background is thought to be less than a few hundred Mpc, although this estimate is very uncertain because of our poor knowledge of the diffuse infrared background. Nevertheless, for a cosmological population of astrophysical objects such as GRBs, absorption is expected to reduce the detected flux of TeV photons. The detection could therefore be dominated by the closest bursts.

We first compute $N_\mu(E_\gamma, > E_\mu)$, the number of muons with energy in excess of $E_\mu$, produced in a photon shower of energy $E_\gamma$. The muon rate is subsequently derived by convolution with the gamma-ray spectrum,

$$N_\mu(> E_\mu) = \int_{E_{\gamma\rm th}}^{E_{\gamma\max}} dE_\gamma \, N_\mu(E_\gamma, > E_\mu) \frac{dN_\gamma}{dE_\gamma} . \quad (7)$$

Here $E_{\gamma\rm th}$, the minimum photon energy needed to produce muons of energy $E_\mu$, is given by $E_{\gamma\rm th} \sim 10 \times E_\mu/\cos\theta$, where $\theta$ is the zenith angle at which the source is observed.

Our results imply that the operating AMANDA, Baikal, and MILAGRO detectors can do GRB science in an energy range not covered by astronomical telescopes. While detection may be marginal for the most conservative estimates of the high-energy GRB flux, this will not be the case for future detectors on the drawing board such as AMANDA II, IceCube (AMANDA 1998), and Antares (Arpesella 1998).

### 3.1. *AMANDA and Lake Baikal as Gamma-Ray Telescopes*

The vertical threshold for muon detection in the AMANDA detector at a 1.5 km depth is $\sim$350 GeV. For the shallower depth of Lake Baikal this threshold is $\sim$150 GeV. For threshold energies in this range we may make use of parameterization (1), which is adequate for $E_\mu$ between 0.1 and 1 TeV (Halzen et al. 1997). As previously mentioned, absorption of gamma rays in cosmological backgrounds has to be taken into account, as well as the source distribution of GRB in redshift $z$:

$$N_\mu(> E_\mu)(\text{yr}^{-1}) = A(\text{m}^2)\Delta t \, \frac{1}{2} \, t \times \int_0^{\theta_{\max}} \int_0^{z_{\max}} \int_{E_{\gamma\min}}^{E_{\gamma\max}} dz \, dE_\gamma \, \frac{F_\gamma}{E_\gamma^{\gamma+1}} \, e^{-\tau(E_\gamma, z)} \times \frac{2.14 \times 10^{-17}}{E_\mu} \left(\frac{E_\gamma \cos\theta}{E_\mu}\right) \times \sin\theta \, \frac{dR_{\rm GRB}}{dz}(z) , \quad (8)$$

where $E_\mu$ is the vertical threshold energy of the detector, in TeV units. $\tau(E_\gamma, z)$ is the optical depth of a photon with energy $E_\gamma$ originating at a distance $z$. For illustration, we will use the diffuse photon background of reference (Stecker & de Jager 1998) throughout. $dR_{\rm GRB}/dz$ is the cosmological distribution of GRB, i.e., the number of GRBs per unit time and distance $z$. Following Mannheim, Hartmann, & Funk (1996) and Piran (1998), we will assume cosmologically distributed standard candles with no source evolution. The GRB distribution has been normalized to 365 events per year observed by BATSE below a redshift of $z_{\max} = 2.1$ (Mannheim et al. 1996). $A$ is the effective area of the detector. The dependence of $F_\gamma$ on the characteristics of the burst is given by equation (6), which can be used for scaling purposes.

AMANDA and Baikal observations require a time stamp for background rejection; they can therefore only see bursts previously observed by satellite experiments. The BATSE rate of one burst per day corresponds to an isotropic distribution on the sky of 365 bursts per year. For the most conservative estimate with $E_{\gamma\max} = 10$ TeV and a "standard" burst with total energy $E_{\rm GRB} = 3 \times 10^{52}$ ergs and a spectral index $\gamma = 1$, we predict one muon per year correlated in time and direction with GRB for the AMANDA telescope and 89 per year for the most conservative GRB flux estimate normalized to the observed diffuse GeV cosmic background (Vázquez 1998; Totani 1998). The unknown energetics of GRBs above GeV may yield much higher rates; see, for instance, Totani (1998). The results are subject to the uncertainty associated with the absorption on infrared light, which we computed following Stecker (Stecker & de Jager 1998). The rates are essentially the same for the Lake Baikal experiment.

Interestingly, the muon counts are similar for a single nearby burst at redshift $z = 0.1$, and a flux of a few muons or more in a 1 s interval in coincidence with a gamma-ray burst provides a striking experimental signature which is hard to miss. In Figures 1 and 2 we plot the number of muons per burst versus spectral index $\gamma$ for a burst at $z = 0.1$. We assume again that the photon spectrum extends only to $E_{\gamma\max} = 10$ TeV with a total energy $E_{\rm GRB} = 3 \times 10^{52}$ ergs. We assumed an effective area of $A = 10^4$ m$^2$ for AMANDA and $10^3$ m$^2$ for the Lake Baikal detector

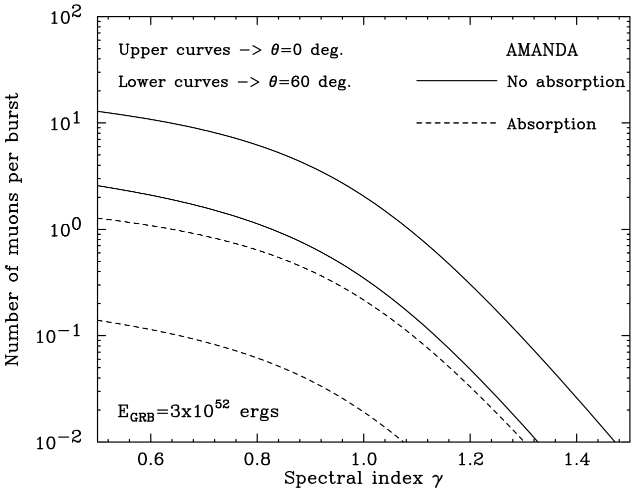


FIG. 1.—Number of muons in AMANDA per "standard" burst (see text) at $z = 0.1$ as a function of the spectral index of GRB photon spectrum. Curves are shown for different zenith angles of observation and with and without absorption of photons in the infrared background.

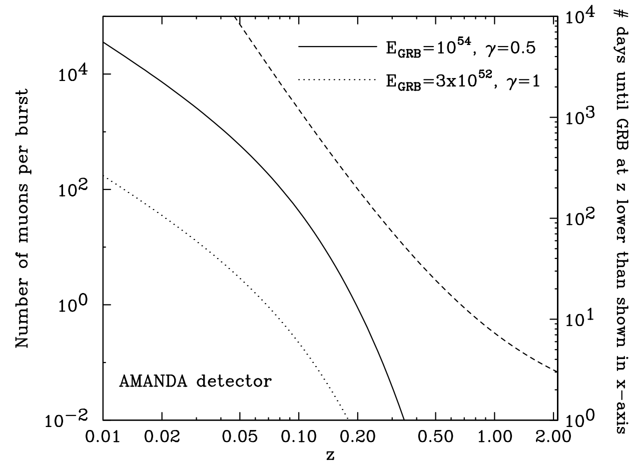


FIG. 3.—Number of muons per burst in AMANDA as a function of redshift. Results include absorption by the infrared background and are shown for a "standard" burst and a burst normalized to the observed GeV diffuse gamma-ray background. The dashed line shows the time in days until a burst occurs in the field of view of AMANDA, at a $z$ value lower than the one indicated on the horizontal axis.

(AMANDA 1998; BAIKAL 1998; Sokalski & Spiering 1992; Spiering 1998). The results are shown with and without absorption on infrared light. Also the dependence of the rate on zenith angle $\theta$ is illustrated. The rapid decrease of the number of events when $\theta$ increases is a consequence of the increase of the energy threshold because muons have to penetrate an increasing amount of matter to reach the detector. The smaller area of Baikal is compensated by its lower muon threshold, especially for larger zenith angles.

In Figure 3 we show the rate per burst in AMANDA detector as a function of redshift for a model with spectral index $\gamma = 1$ and total energy $E_{\rm GRB} = 3 \times 10^{52}$ ergs. Also shown is the flux for energetics (Vázquez 1998), which accommodates the diffuse GeV background. Absorption has been included, as in Figures 1 and 2. Shown as a dashed line is the number of days toward a burst at the corresponding redshift assuming the GRB distribution of Mannheim et al. (1996).

An important question is whether the signal is observable given the large background of muons of cosmic-ray origin

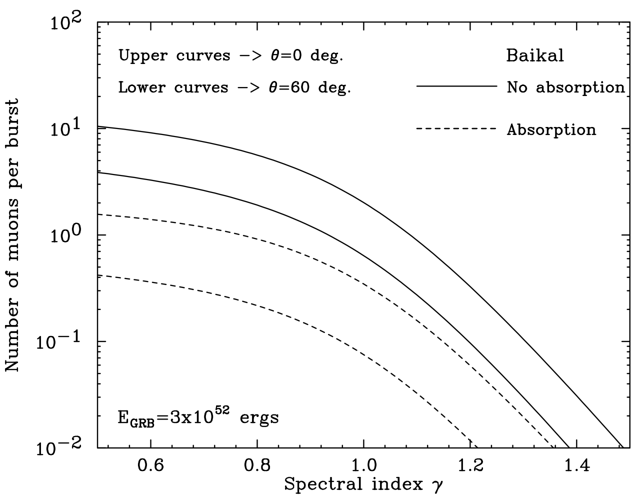


FIG. 2.—Same as Fig. 1 for Lake Baikal detector

penetrating the detectors. In this respect the great advantage of GRB detection is that the detector integrates background only for the short duration of the burst, typically 1 s. Furthermore, the background can be limited to a circle in the sky of angle $\delta\theta$ around the direction of the burst. Here $\delta\theta$ is the angular resolution of the detector, which is typically a few degrees. It can be sharpened up by quality cuts, but this inevitably results in a loss of effective area. The muon background intensity from cosmic-ray showers $I_\mu(\theta)$ has been measured (AMANDA 1998; BAIKAL 1998; Sokalski & Spiering 1992; Spiering 1998). The muon background at zenith $\theta$ is given by

$$\text{Noise} = I_\mu(\theta) \times A \times \delta\theta^2 \,. \qquad (9)$$

The signal–to–square root of noise ratio then scales as

$$\frac{\rm S}{\sqrt{\rm N}} = \frac{\sqrt{A}}{\delta\theta}\,, \qquad (10)$$

which simply expresses that the sensitivity is improved for larger area and for better angular resolution. Note that our search is not sensitive to photons produced over timescales much larger than seconds, for instance, to photons possibly produced by propagation of the external shock in the interstellar medium.

In Table 1 we present the number of muons per burst detected by AMANDA. The first column is the redshift of the burst, and the second (third) column is the signal without (with) absorption of gamma rays in intergalactic backgrounds. In each column the results are given for zenith angle $\theta = 60$ and $\theta = 0$. The fourth column gives the signal–to–square root ratio of noise corresponding to the third column. The fifth column shows the time in days between bursts with $z$ lower than the value shown in the first column. We here assumed a "standard" burst with spectral index $\gamma = 0.8$ and $E_{\gamma\rm max} = 10$ TeV. The role of absorption for gamma-ray detection is evident. Nearby bursts with $z < 0.1$ provide the best opportunity for detection. Their frequency is of the order of one burst every 2–3 yr.

TABLE 1

EVENT RATES IN AMANDA DETECTOR

| $z$ | Muons per Burst | Muons per Burst | Signal to $\sqrt{\text{Noise}}$ | Time (days) |
|---|---|---|---|---|
| 0.05 ...... | 5–25 | 2–12 | $\frac{60}{\delta\theta} - \frac{133}{\delta\theta}$ | 8400 |
| 0.1 ....... | 1–6 | 0.06–0.6 | $\frac{1.8}{\delta\theta} - \frac{6.6}{\delta\theta}$ | 1200 |
| 0.5 ....... | 0.05–0.25 | $5 \times 10^{-10}$ to $3 \times 10^{-6}$ | $\frac{1.5 \times 10^{-8}}{\delta\theta} - \frac{3.3 \times 10^{-5}}{\delta\theta}$ | 24 |
| 1.0 ....... | 0.01–0.05 | 0–$3 \times 10^{-11}$ | $0 - \frac{3.3 \times 10^{-10}}{\delta\theta}$ | 8 |

NOTES.—For models accommodating the diffuse GeV background the rates are larger by 2 orders of magnitude. The first column is the redshift of the burst, and the second (third) column is the signal without (with) absorption of gamma rays in intergalactic backgrounds. In each column the results are given for zenith angle $\theta = 60$ and $\theta = 0$. The fourth column gives the signal–to–square root of noise ratio corresponding to the third column. The fifth column shows the time in days between bursts with $z$ lower than the value shown in the first column.

### 3.2. *The MILAGRO Telescope*

The muon energy threshold for MILAGRO detector is only 1.5 GeV. It has an effective area $A = 1.5 \times 10^3$ m$^2$ and an intrinsic angular resolution of about 3°. This requires the use of a 4°.7 bin size to collect $\sim$70% of the gamma-ray events in which the muon background from cosmic rays is $\sim$900 Hz (Yodh 1995). In Table 2 we present the number of muons per burst observed by MILAGRO for two maximum energies and two spectral slopes of the photon spectrum. The results are shown corresponding to the "standard" burst energy and to the energy required in the models in which GRBs are responsible for the diffuse extragalactic gamma-ray background. The absorption of the photon flux has not been taken into account. MILAGRO with a threshold for muon detection as low as 1.5 GeV is sensitive to photons with energy $\sim$15 GeV, which are not absorbed in the intergalactic backgrounds. Therefore detection of bursts at large redshifts is possible. For a spectral index $\gamma = 1$, equal amounts of energy are stored in every logarithmic interval. The number of low-energy photons will be larger than high-energy ones by the ratio of energies. On the other hand, the number of muons in a photon shower scales roughly with its energy. This will compensate the contribution to the number of muons from low- and high-energy photons if it were not for absorption that predominantly reduces the high-energy part of the photon spectrum. Counting of low-energy muons may therefore be more efficient than reconstruction of the photon shower, the conventional MILAGRO method, because it raises the threshold to hundreds of GeV. This is especially true for the detection of the average ($z \sim 1$) GRB.

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TABLE 2

SENSITIVITY OF MILAGRO TO A GRB AT ZENITH ANGLE $\theta = 0$ FOR SEVERAL ASSUMPTIONS ON TOTAL ENERGY, SPECTRAL INDEX, AND MAXIMUM ENERGY

| $E_{\text{GRB}}$ (ergs) | Spectral Slope $\gamma$ | $E_{\gamma\max}$ (TeV) | Signal per Burst | Signal to $\sqrt{\text{Noise}}$ |
|---|---|---|---|---|
| $3 \times 10^{52}$ ...... | 1.0 | 10. | 24 | 0.82 |
| | 0.8 | 10. | 57 | 1.9 |
| | 0.5 | 10. | 95 | 3.2 |
| | 1.0 | 0.1 | 2.3 | 0.08 |
| | 0.8 | 0.1 | 5.0 | 0.16 |
| | 0.5 | 0.1 | 9.2 | 0.3 |
| $10^{54}$ .......... | 1.0 | 10. | 785 | 26.4 |
| | 0.8 | 10. | 1920 | 64.0 |
| | 0.5 | 10. | 3230 | 107.4 |
| | 1.0 | 0.1 | 75 | 2.5 |
| | 0.8 | 0.1 | 165 | 5.6 |
| | 0.5 | 0.1 | 305 | 10.0 |

NOTE.—Absorption of gamma rays is not included.

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