MILAGRO at 10 GeV

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1 Introduction

Although MILAGRO is optimized for air showers in the 1 TeV range, most of the particles hitting the pool come from showers produced by much lower energy primaries. Although these showers may not be reconstructible or produce triggers, by monitoring the rate of particles hitting the MILAGRO pool, it is possible to measure the overall flux of low energy particles. Phenomena like GRBs, exploding black holes[1], or solar flares may produce a short term increase in the low-energy particle flux, which may be detected by monitoring the PMT hit rates in the pool. The absence of a rate increase when a supernovae is detected could also be used to set limits on prompt GeV photon emission from supernovae.

Because the PMT rates can be expected to drift with time, temperature, atmospheric pressure and other factors, this technique is probably not applicable for long term sources, but it should be useful for short episodes of an hour or less. If a short term rate increase is time coincident with some other event, such as a burst of TeV gamma rays, a BATSE burst, or a solar flare, it may be quite confidently linked with an increase in the primary particle flux.

A few experiments have used similar techniques. The EAS-TOP collaboration has set a limit on gamma ray bursts[2] in the 1-50 GeV energy range. It is worth noting that, in their most recent publication, they report on a 10.6 σ , roughly 2 second long increase in the count rate, something that they say could be due to a gamma ray burst. The AKENO collaboration has reported[3] a 20 minute long, 4σ rate increase simultaneous with a solar flare; they attribute the increase to 10+ GeV neutrons. Compared to these two experiments, MILAGRO will be orders of magnitude more sensitive. The AKENO sensitive area was only 182.6 m^2, of which only 10% was used for this analysis, due to electronics limitations. EAS-TOP covers only 290 m^2, and both are at lower altitudes than MILAGRO. In addition, both are scintillation detectors, and less sensitive to the photons that make up over 90% of the particles reaching the ground.

This memo will estimate the MILAGRO sensitivity to 10 GeV photons.

2 Sensitivity Calculations

For pedagogical purposes, I begin with a simple calculation, assuming that MILAGRO sees a 1 second long burst, with the tube dark noise at 10 kHz, a 25% higher rate than is seen in the pools. Since any hits should be evenly distributed over the pool, all of the tubes will be lumped together; any real astrophysical burst should show comparable increases in all the tubes.

Table 1: Average number of particles and average energy of particles reaching the ground.

Energy	0^o	15^o	30^o
4 GeV	0.14 / 16.7 MeV	0.09 / 15.2 MeV	0.01 / 12.6 MeV
10 GeV	0.93 / 18.7 MeV	0.47 / 16.5 MeV	0.15 / 15.2 MeV
20 GeV	2.33 / 19.9 MeV	1.54 / 17.1 MeV	0.52 / 15.0 MeV
40 GeV	7.18 / 18.9 MeV	5.01 / 18.4 MeV	1.76 / 16.8 MeV
100GeV	30.5 / 20.2 MeV	23.3 / 20.1 MeV	7.7 / 18.6 MeV

The baseline design MILAGRO top layer has 408 PMTs, implying a total dark rate of 4.1 MHz. For a 1 second burst, the uncertainty is 2000 counts. For conservatism, I will require a 10σ increase, or 20,000 counts. Taking the MILAGRO sensitive area as 5000 m^2 and assuming that MILAGRO is 100% sensitive implies that MILAGRO will have a 1 second sensitivity of 4 particles m^{-2} hitting the detector. For longer bursts, the flux sensitivity is 4 $/\sqrt{T}$ particles/m^2/s, where T is the burst duration in seconds. The $\sqrt{T}$ dependence occurs because the sensitivity scales inversely as the square root of the total counts.

To compute the sensitivity to photons at the top of the atmosphere, it is necessary to use a Monte Carlo. I have used EGS, modified to include the earth's magnetic field. The results are shown in Table 1. Because short bursts are of interest, fixed zenith angles of 0^o, 15^o, and 30^o were chosen, with the azimuthal angles chosen randomly (they are relevant only when considering the geomagnetic effects). Depending on energy and angle, between 1000 and 10,000 showers were generated for each combination. The number of particles reaching the ground rises much faster than the incident energy, while the average energy per particle reaching the ground rises slowly. In all cases, at least 85% of the particles hitting the ground are photons. The particles are spread out enough that it is quite unlikely that two particles will hit a single MILAGRO PMT.

From Table 1, it is clear that a reasonable first estimate of the overall sensitivity can be found by assuming that MILAGRO receives 1 PMT count/incident photon above 10 GeV. Then, the MILAGRO top of the atmosphere sensitivity to vertically incident photons above 10 GeV is also $4/\sqrt{T}$ particles/m^2/s.

This sensitivity should be compared to MILAGRO's sensitivity to sources of high energy (TeV) photons that trigger the detector. The higher energy photons arrive at a much lower rate, but have much lower backgrounds because directional information is available. For simplicity, this initial calculation compares the 1 second burst flux above 10 GeV (non-triggered) with the flux above 1 TeV (triggered), since at 1 TeV, the MILAGRO effective area of 3000 m^2[4] is comparable to the physical area. Since recent simulations have predicted a higher light yield than indicated in the proposal, the effective area at 1 TeV will be taken equal to the 5000 m^2 physical area.

To compare the sensitivity at the two energies, a spectral index is required. Two

Table 2: Spectral exponents and relative flux for two spectral sources. Relative flux is merely the ratio of the integral fluxes above 10 GeV and 1 TeV.

Source	Exponent(Differential)	Relative Integral Flux
Cosmic Rays	-2.76	3300
May 3, 1991 GRB	-2.24	300

possible source indices are shown in Table 2.

For the cosmic ray spectrum, the 4 photons per m^2 sensitivity is equivalent to a time integrated vertical flux sensitivity of $N(E> E_c) = 230\ E_c^{-1.76}/m^2$, or a differential flux of $dN/dE = 405\ E^{-2.76}$ /GeV/m^2, where the energies are in GeV. This spectrum predicts that the flux above 1 TeV, over the MILAGRO pool, is 6 events. For MILAGRO, the the probability of getting 6 triggered events from one direction in 1 second, assuming an expected background of 0.5 Hz, is about 1.3×10^{-5}, or about 4.7σ, significantly less than the 10σ the scalars would register from the same burst.

It should be noted that, at 10 GeV, it is not meaningful to compare with the absolute cosmic ray flux, because the GeV cosmic ray flux is heavily affected by geomagnetic effects, the solar wind and other heliospheric effects.

While these numbers only apply for photons, similar calculations could be done for low energy neutrons, which should yield mostly muons at the surface.

A better model can be made by calculating the pond hit rate using the actual energy spectrum and detection efficiency and the rates given in Table 1. An appropriate parameterization is

$$N_{PMTs} = \int \epsilon N_{part}(E) \frac{dN}{dE} dE$$

where ϵ is the probability of detecting a particle hitting the pool, and N_{part} is the number of particles hitting the pool as a function of incident photon energy.

For simplicity, it is possible to crudely parameterize the hit rates in Table 1 using $N_{part}(E) = k(E/10GeV)^{1.6}$ where k=0.93, 0.47 or 0.15 respectively for the three zenith angles. This approximation should be accurate within 40%. It is unfortunate, but unavoidable, that when this is multiplied by the $E^{-2.76}$ differential cosmic ray spectrum, the extrapolated sensitivity depends strongly on the exact spectral exponent.

The pond efficiency was determined by David Williams using the 10 GeV vertical photon Monte Carlo mentioned above, together with the UCSC MILAGRO simulation. He used the 'baseline' MILAGRO, except with the phototubes at a depth of 2 meters. Of the 930 particles reaching the ground (from 1000 10 GeV photons at the top of the atmosphere), 532 PMTs fired. Of the PMTs that fired, the mean number of p.e.'s was 2.4, with 65% of the hits consisting of a single photoelectron. The 532 hit PMTs imply a particle detection efficiency of 55%. It is also worth noting that sometimes a single particle could cause more than 1 phototube to fire; 532 represents the total number of hit phototubes. These hit phototubes came from only 332 of the

930 original particles.

One rough check on ϵ comes by using the canonical 1 detected photoelectron per 5 cm pathlength in water. A minimum ionizing particle loses about 10 MeV in traversing 5 cm of water, so for an average particle energy of 18 MeV, we expect 1.8 p.e. per particle, or about 1670 photoelectrons/1000 10 GeV photons, not too far from the Monte Carlo prediction of 1288 photoelectrons.

For the remainder, I will assume a detection efficiency of 55%. This could be scaled by the average energy of particles reaching the pond, but because the average energy of the particles hitting the pond changes so little with incident energy, this detail can be neglected. So,

$$N_{PMT} = \int 0.55k(\frac{E}{10GeV})^{1.6}\frac{dN}{dE}dE$$

The value of this integral depends on the lower cutoff energy. I will somewhat arbitrarily cut off the integrals at 2 GeV, which is half the energy of the lowest Monte Carlo point. For the cosmic ray spectrum, sensitivity calculations are almost independent of the lower energy cutoff.

In addition, some consideration should be given to an upper energy cutoff, at an energy where a single shower saturates the pond. As will be discussed in the next section, 500 GeV is an appropriate, if somewhat conservative energy.

Using the above photon spectrum and the same 4/m^2 hit rate, we find a vertical sensitivity to a flux of N(E> E_c) = 52 $E_c^{-1.76}$ (GeV) /m^2, or a differential flux of dN/dE = 90 $E^{-2.76}$ /GeV /m^2, or 4.5 times the sensitivity indicated by the simpler calculation. At this flux, there is an average of 0.8 events above 1 TeV; with these assumptions the MILAGRO singles rate is more sensitive to short bursts than a search using triggered events.

3 Gamma Ray Bursts

Since gamma ray bursts are known to occur, producing photons up to at least several GeV, they are a good subject for a more careful analysis, both compared to MILAGRO's triggered sensitivity, and to the known GRB energy output.

For most of this section, the May 3, 1991 burst detected by EGRET will serve as a benchmark. EGRET measured a flux at 2 MeV of 1.9 photons/MeV-cm^2-sec. with a differential spectral index of -2.24 and a burst length of about 5 seconds[5]. This burst is the 2nd strongest detected by EGRET; the Superbowl burst was both stronger and had a harder spectrum. However, the May 3 burst will serve as a benchmark.

Because the burst lasted about 5 seconds, and the overall flux required to achieve 10σ significance using the simple model is 5/m^2. In trying to apply the more sophisticated model used above, one complication appears: the integral $\int E^{-2.24}E^{1.6}dE$ diverges. In reality, the integral is cut off by a number of factors: any cutoff in the production or transport mechanisms, the failure of the $E^{1.6}$ parameterization for the number of particles, the saturation of the pool PMTs (each PMT can only record 1 count at a time), and the limitation that, at high enough energies, at least one event must hit the pool.

With the possible exception of the production and transport mechanisms, these are all soft cutoffs. The $E^{1.6}$ parameterization fails at a few TeV; at 500 GeV, it is within 15% of EGS, but at 5 TeV it overestimates the particle count by a factor of 2.5. In reality, the average particle energy in a 5 TeV shower is up to about 30 MeV, so if we included the rising average particle energy effects in the efficiency calculations, the $E^{1.6}$ approximation would probably survive to at least 5 TeV.

The pool will begin to saturate when most of the PMT's have been hit. 300 PMT's (75% of the pool) is a reasonable, albeit rather arbitrary saturation point. With the 55% particle detection efficiency, this is equivalent to 545 particles. This occurs at 510 GeV. This procedure is a gross simplification, because at these energies the shower extends over a much larger area than the pool, with saturation occurring near the core at much lower shower energies, but with the remainder of the shower extending over a much larger area than the pool. Nevertheless, since these two factors work in opposite directions, and since I will cut the integral off abruptly at this point, it isn't an unreasonable choice. So, I will adopt 500 GeV as a reasonable cutoff energy. It also fairly nicely matches the lower end of MILAGRO's sensitivity via triggered events. If a signal is observed, a detailed Monte Carlo will be needed to study this cutoff and the detector response above 500 GeV.

The cutoff due to the source or photon transport is one of the things we would like to measure.

Converting the EGRET flux to more usable differential flux units of dN/dE = $85E^{-2.24}$/GeV/m^2, and taking the burst to occur directly overhead leads to

$$N_{PMT} = \int_{2GeV}^{500GeV} 0.55(\frac{E}{10GeV})^{1.6} 85E^{-2.24}/m^2 dE = 25/m^2$$

This rate is easily detectable, amounting to a 28σ increase over the 5 seconds. If the burst occurred at a 15^ozenith angle, it be detectable at about 14σ.

Of course, MILAGRO would see this burst easily in the triggered data. The equivalent integral flux of $N(E > E_c) = 68E_c^{-1.24}(GeV)/m^2$, predicts 65 events above 1 TeV in 5000 m^2. If, as is likely, MILAGRO does not see a significant excess in triggered events, then the scalar count rate could be used to find the physics based GRB cutoff energy. For example, if the spectrum cut off abruptly at 100 GeV, the count rate would be decreased by about a factor of 2. With a 50 GeV cutoff, the rate would go down by roughly a factor of 3. A measurement of either would be an important milestone in understanding GRBs.

At CYGNUS energies (taking E_c = 50 TeV) and the CYGNUS area (20000 m^2) only 4 events are predicted, very close to the detection threshold. This number differs from the 6 events calculated earlier by Richard Schnee because Richard used a more detailed effective area calculation.

The flux from the May 3rd burst seems inadequate to explain the 10σ increase seen by EAS-TOP. Comparison of EAS-TOP[2] and MILAGRO Monte Carlos shows that EAS-TOP is about a factor of 2 less sensitive due to the lower altitude. Beyond that, it is about a factor of 5(?) less sensitive because it is not sensitive to photons. So EAS-TOP should have seen an increased count rate of order $3/m^2$, while their observed rate increase corresponded to $34/\mathrm{m}^2$.

Given that MILAGRO could see two bursts observed by EGRET, what about other bursts? Recently, BATSE published their spectra on 54 bursts[6] obtained during the first 12 months or running. The bursts were selected on the basis of the quality of spectral data, which meant they generally comprised the strongest bursts, excluding only a few bursts which were too short for the spectrometer electronics. In this paper, BATSE fit the spectra accumulated over the whole burst, but commented that the spectra evolved with time, generally from hard to softer. So, if part of the spectrum is harder, then these averaged spectra could possibly understate the probability of detection at higher energies. 45 of the 54 bursts were classified as complex.

They used their smaller spectral detectors, which generally had useful data up to a few MeV. They fit the high energy part (above a typical breakpoint of a few hundred keV) to a power law, with the exponents constrained between -1.5 and -5.0. The May 3, 1991 burst falls in the middle of the range, with BATSE measuring an index of -2.145 compared with EGRETs -2.24, well within the estimated uncertainties. Including the one burst whose fit exponent limited at -1.5, 20 of the 54 bursts had spectra harder than -2.145. If these spectra extend up to high enough energies, 19 of these bursts would be detectable by MILAGRO through triggered events, and 11 should be visible in the scalars. If the spectrum cuts off below 500 GeV, then the signal will either be visible in the scalars, or the scalars can be used to set interesting limits on the cutoff.

Because these spectra are so hard, the directional information provided by triggered events overcomes the rate advantages of the scalars, and MILAGROs sensitivity is greatest by using triggered events. Of course, if the spectrum cuts off in the 50-500 GeV region, the scalars are the only way for MILAGRO to observe GRBs.

19 events/year is a high enough rate that if MILAGRO waits long enough, a strong enough GRB should occur in its field of view; when that occurs MILAGRO will be able to see it or set a limit on it's spectral cutoff.

At least 7 of these events would be easily visible to CYGNUS if the spectrum extends to 50 TeV and they occurred overhead. Richard will be saying more about this in parallel.

4 Can MILAGRO be improved?

I have considered two possible ways to increase MILAGRO's sensitivity to low energy particles. Unfortunately, neither seems to give much improvement. The first is to measure the rates at a discriminator threshold higher than 1 p.e. I measured the rates as a function of discriminator threshold in the center CYGNUS pool; they are shown in Figure 1. The PMT signal was amplified by 100 with two Phillips 776 X10 amplifiers (the usual one, plus a second one), and fed through a LeCroy 428F fanout and a LeCroy 620CL discriminator into a scalar. One photoelectron corresponded to about 100 mV. It is worth noting that these measurements were taken while the LAMPF accelerator was starting up, and may be somewhat affected by stray radiation.

These numbers can be compared with the expected number of p.e. due to low energy particles. The Monte Carlo predicts that 65% of the PMT hits are single photoelectrons, while figure 1 shows that increasing the discriminator threshold to 2 p.e. will at best reduce the count rate by 60%, so there is no improvement possible by raising the discriminator thresholds.

One could also consider the possibility of trying to count showers by looking for various PMT hit multiplicities in a relatively narrow window (500 nsec or 1μsec). I have not found any combination that gives a clear increase in sensitivity when typical dark rates and muons are included.

5 Hardware

The hardware required for scalars is quite minimal. CAMAC, VME, and FASTBUS scalars are available, for about \$100 per channel. To reduce the cost, outputs from several PMT discriminators could be logical-ORed to feed one scalar. With 8:1 ORing, 51 scalars are required (4 CAMAC or VME modules), costing about \$6K if we use LeCroy 1528's. In addition, some simple analog and digital ORing circuitry is needed; these costs will be negligible if the circuitry is initially designed into the experiment. One slight complication is the undesirability of ORing adjacent tubes; otherwise a single particle incident on the pond, which fires two adjacent tubes within the scalar deadtime will only result in a single count if the two PMTs are ORed to the same scalar.

In addition to the physics interest, monitoring the PMT singles rates is a useful diagnostic. It provides a measure of temperature and pressure drifts, and can provide quick, hard evidence of many types of impending catastrophes, such as light leaks.

6 The CYGNUS Pools.

Since the CYGNUS pools are intended as a MILAGRO prototype, it is worth considering whether we should instrument them now. The pools have a total area of 200 m^2, 1/25 of that of MILAGRO. They are also at a lower altitude, slightly higher than EAS-TOP. Comparison of the efficiencies shown above with those given by EAS-TOP indicates that the altitude difference between MILAGRO and CYGNUS/EAS-TOP produces about a factor of 2 loss of efficiency, So, the pools have about 1/10 the sensitivity of MILAGRO, 1/5 for the area, 1/2 for the altitude).

Despite the factor of 10 loss of sensitivity compared with MILAGRO (5 for the area, 2 for the altitude), the pools are still sensitive enough to put constraints on some of the BATSE bursts discussed in section 3. The extrapolated flux from 3 of the 54 bursts would be cleanly ($> 10\sigma$) visible in the pools if the spectra extend to the 100 GeV region. In particular, if the pools had been instrumented with scalars in November, 1991, we would have either seen or been able to set useful limits on burst 1B911104.

Despite the comparable altitude and slightly larger EAS-TOP area, the pools should be more sensitive than EAS-TOP because the water Cherenkov technique is several times more sensitive to the low energy photons that comprise most of the incoming flux. The one major disadvantage of the pools is that they are sensitive to accelerator induced radiation, and so are only usable for physics when the accelerator is off.

The hardware requirements are modest; as of mid-July LEEP had enough CAMAC scalars available to instrument every tube. It is an open question as to whether the scalars should be included in the CYGNUS data stream, or read out by a separate computer and CAMAC system.

7 Conclusions

Including scalars to measure the PMT singles rates can significantly enchance MILAGRO's physics reach, down to the 10 GeV region for short term events. While probably inadequate alone, the scalar rates could be used to increase the statistical significance of any detected burst of 1 TeV gamma rays. In addition, any rate increase (or absence thereof) in coincidence with an independently detected gamma ray burst, black hole explosion or solar flare can be used to provide flux information in the 4-100 GeV region. Finally, the scalars will be useful in monitoring the experiment.

If the harder GRB spectra seen by BATSE extend up to high enough energies, then MILAGRO will either detect these bursts or set a limit on their spectral cutoff. Because the CYGNUS pools are also sensitive to these bursts, the pools should be instrumented with scalars for use after the end of this accelerator run.

I would like to thank Don Coyne, David Williams and Richard Schnee for useful discussions, and David Williams and Tom Yang for their efforts with the Monte Carlo.

8 References

[1] D.G.Coyne and R. Somerville, work in progress.

[2] EAS-TOP Collaboration, "Search for > 10 GeV and > 80 TeV Cosmic Gamma

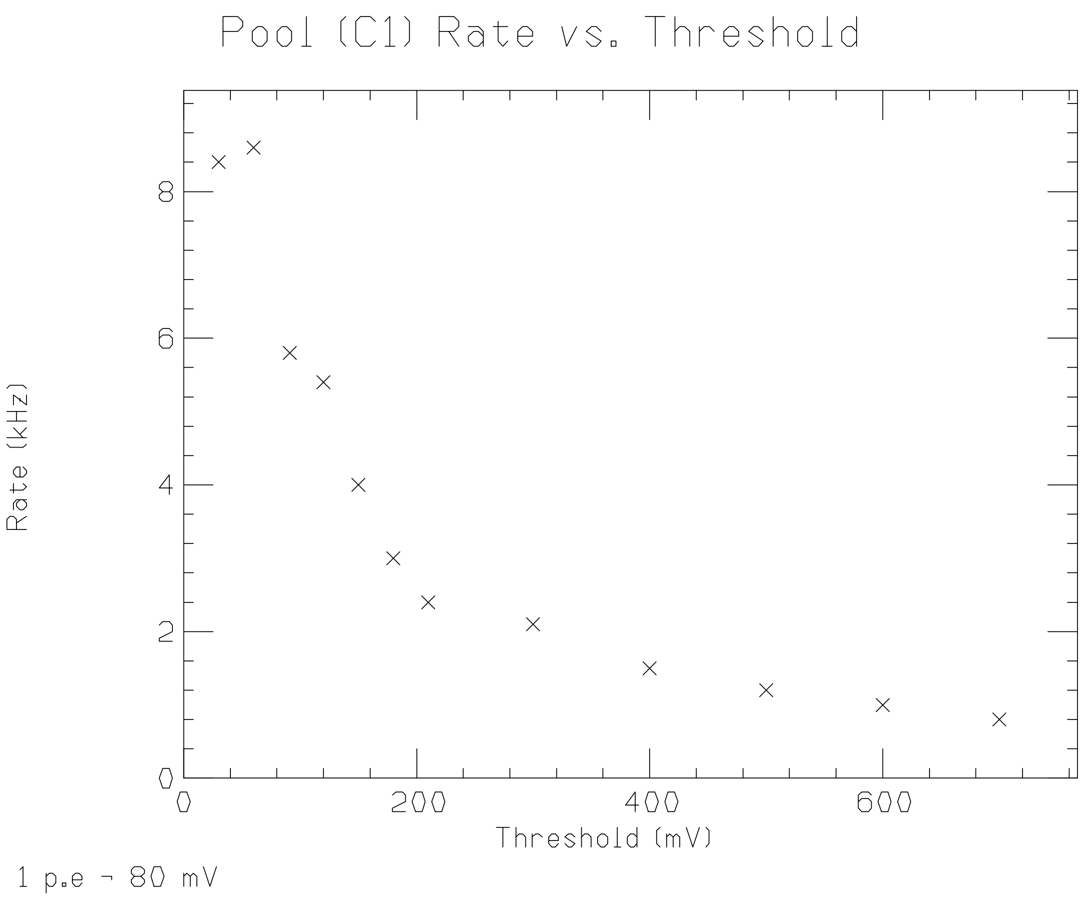
Pool (C1) Rate vs. Threshold
Rate (kHz)
0
2
4
6
8
0
200
400
600
Threshold (mV)
1 p.e ¬ 80 mV

Figure 1:

Ray Bursts, LNGS 93/66, submitted to the XXIIIrd ICRC; M. Aglietta *et al.*, "Search for cosmic γ-ray bursts in the 1-50 GeV energy range", LNGS 92/24.

[3] N. Chiba, *et al.*, "Possible Evidence for ≥ 10 GeV Neutrons Associated with the Solar Flare of June 4th of 1991," Astroparticle Phys. **1**, 27 (1992).

[4] The MILAGRO proposal. The effective area at 1 TeV is taken from Figure 3.3.1.a.

[5] E. J. Schneid *et al.*, "EGRET Observations of Gamma Ray Bursts", contributed to the Compton Observatory Symposium, Washington University, St. Louis, October, 1992.

[6] D. Band *et al.*, "BATSE Observations of Gamma-Ray Burst Spectra. I. Spectral Diversity." Ap. J. **413**, 281 (1993).