THE MILAGRO GAMMA RAY OBSERVATORY:

Gaurang B. Yodh
Department of Physics, University of California Irvine
Irvine, CA, USA,92717

Representing The MILAGRO Collaboration

H.S. Ahulwalia,[9] S. Barwick,[2] D. Bauer,[6] S.D. Biller,[2] D. Caldwell,[6] M. Cavalli-Sforza,[4] C.Y. Chang,[1] M.L.Chen,[1] P. Chumney,[2] D.G. Coyne,[4] B.L. Dingus,[11] C.L. Dion,[1] D.E. Dorfan,[4] R.W. Ellsworth,[5] S.J. Freedman,[10] B.K. Fujikawa,[10] T.J. Haines,[3] C.M. Hoffman,[3] L.A. Kelley,[4] S. Klein,[4] A. Lu,[6] A.I. Mincer,[8] D.E. Nagle,[3] P. Nemethy,[8] T.J. O'Neill,[7] V.D. Sandberg,[3] G. Sanders,[3] S. Schaller,[3] D.M. Schmidt,[3] A. Shoup,[2] C. Sinnis,[3] O.T. Tumer,[7] D.H. White,[3] D.A. Williams,[4] T. Yang,[4] S. Yellin,[6] G.B. Yodh,[2] and A. Zych[7]

Abstract

Milagro will be the first water-Cherenkov detector specifically built to study extensive air showers. It is being built in an existing man-made pond 60m x 80m by 8m, located in the Jemez mountains near Los Alamos, NM. Unlike conventional air shower detectors, which sample less than 1% of the particles which reach detector level, MILAGRO will be totally sensitive to the electrons, photons, hadrons, and muons in the air shower. The threshold of the MILAGRO detector is comparable to atmospheric Cherenkov detectors, however it has several advantages over these optical detectors. MILAGRO is operational 24 hours a day in all weather conditions and it has an open aperture which allows it to view the entire northern sky every day. These capabilities allow for a systematic all-sky survey to be done for the first time at these energies. MILAGRO will measure the Crab spectrum with high significance. In addition, it will detect and measure the spectra from AGN's such as MRK 421. MILAGRO will be the first VHE detector capable of recording Gamma Ray Bursts at energies above 250 GeV. MILAGRO will search for point sources of VHE gamma radiation, both steady and episodic. The physics merits of this detector together with its design and current status are discussed.

[1] *The University of Maryland, College Park,* [2] *The University of California, Irvine,* [3] *Los Alamos National Laboratory, Los Alamos, New Mexico,* [4] *University of California, Santa Cruz,* [5] *George Mason University, Fairfax, Virginia,* [6] *University of California, Santa Barbara,* [7] *University of California, Riverside,* [8] *New York University, New York,* [9] *University of New Mexico, Albuquerque,* [10] *University of California, Berkeley,* [11] *Goddard Space Flight Center, Greenbelt, Maryland*

1 Introduction

Non-thermal high energy gamma ray emission can originate from acceleration or nuclear collisions of cosmic rays of high energy. They can come from synchrotron or curvature radiation in very strong magnetic fields (B$\sim$ 10^{12} gauss), inverse Compton scattering of electrons on ambient photon fields, electron bremmstrahlung, electron-positron annihilation or pi-zero production in nuclear collisions. The power law spectra of proginators give rise to power law spectra for emitted gamma rays. The problem of origin, acceleration and propagation of cosmic rays which give rise to gamma rays at high energies is still an unsolved problem. There are many possible sources of cosmic rays, including supernova(SN) explosions, shock acceleration in ISM from SN shocks, stellar wind shocks, Active Galactic Nuclei(AGN) and Fanaroff-Riley class II radio galaxies. Non-thermal gamma rays can also arise from evaporation of Primordial Black Holes(PBH) in their last gasp producing a burst of 1 to 100 TeV gamma rays in a span of few seconds.

Although gamma rays are undeflected by magnetic fields, they do suffer attenuation due to pair-production processes in collisions with photons either in the source or in their transit from source to the earth. The attenuation length for gamma rays in transit as a function of their energy is shown in Figure 1, which shows that only at energies below 100 TeV one can observe sources beyond 10 Mpc.

Observation of gamma ray sources in the TeV and PeV energy ranges is, therefore, important for understanding the origin of cosmic rays and the nature of the accelerators of cosmic rays. They may shed light on whether Gamma Ray Bursters(GRB) are galactic or cosmological and on the rate of evaporating PBHs. If gamma rays are produced in nuclear collisions they should also give rise to high energy neutrinos for which currently large telescopes are being built, such as AMANDA and DUMAND.

In this paper, I shall give a brief account of current status of TeV and PeV observations and then discuss the prospects of the future with special reference to the capabilities of a new water Cherenkov detector, MILAGRO, currently being built at 8700 feet in New Mexico.

2 Features of High Energy Gamma ray emission

The Compton Gamma Ray Observatory(CGRO) has observed gamma ray emission from various sources from Mevs to 10s of GeV , including that from the Crab, from Geminga, from GRBs and from AGNs. Two general features of gamma ray emission can be discerned from their data: (1) Many of the observed spectra are non-thermal and hard, with differential spectral indices near -2 and (2) the intensity is variable over periods from hours to days. This indicates existence of particle acceleration

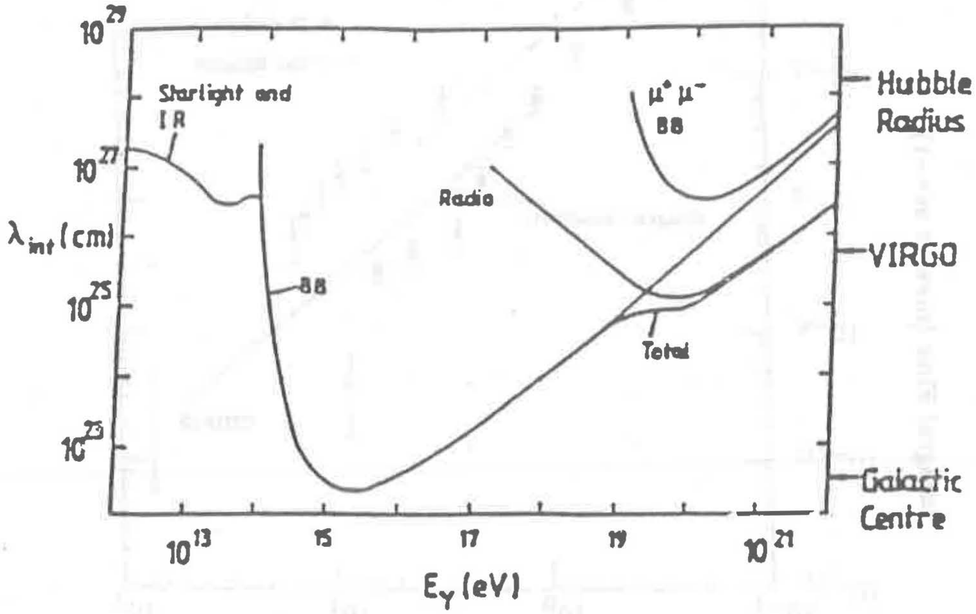

Figure 1: Attenuation length for gamma rays as a function of energy due to ambient interstellar and intergalactic photons in various frequency bands

mechanisms that are efficient and emission regions which are small. Some of the observed spectra by the EGRET instrument extend up to 10 GeV and for GRBs the burst duration for high energy emission is longer than that for lower energies. The sensitivity range of CGRO makes it difficult to answer whether these spectra continue to higher energies. It is of great interest to find out if emission extends to higher energies. If it does then one can put constraints on models of production of gamma rays, understand better the nature of particle acceleration and even estimate the distance to sources based upon attenuation consideration implied by Figure 1.

UHE gamma ray astronomy started with a bang starting with reports of observation of signals from:

- Cygnus X-3, covering a period from late 70s to middle 80s [1,2,3,4,5,6,7,8,9].
- Vela X-1 and LMC X-4 in the southern hemisphere, in the early 80 s[10].

This was followed by the observations of:

- Episodic emission from Hercules X-1 in 1986[11,12,13]
- Episodic emission from the Crab in 1989 [17,18,19] and pulsed emission in the 1984-88 period by Ooty[20]

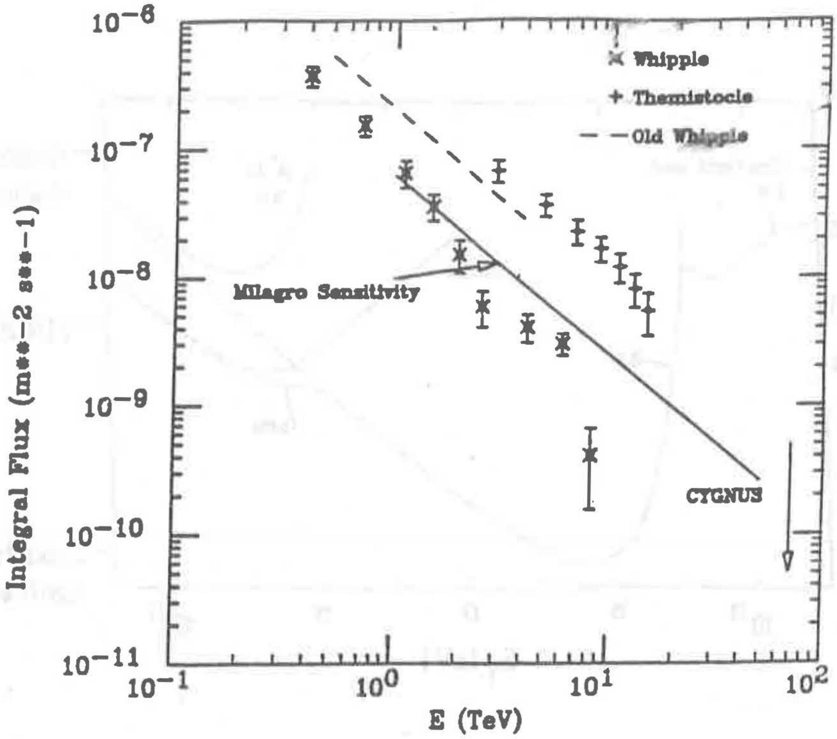

Figure 2: The current results for steady emission from the Crab in the TeV/PeV energy range. The differences between the spectra measured by different techniques indicate the need of independent determination of the spectrum by new techniques such as the water cherenkov telescope Milagro.

- Steady emission from the Crab was observed by the Whipple and the Themistocle experiments[15,16] A summary of results for steady emission from the Crab are shown in Figure 2, which indicates the spread in flux values determined by different air-Cherenkov experiments.

Typical intensity observed by the Kiel, Haverrah Park and the Ooty experiments above 10^{15} eV were as large as $\sim 10^{-14} cm^{-2} s^{-1}$ to $\sim 10^{-13} cm^{-2} s^{-1}$. These signals were not compelling like the 18σ observation of the steady Crab by the Whipple group, although the UHE signals appeared to show correlations with source periods. The observed fluxes implied high intrinsic luminosities for the parent particle beams of the order of 10^{38} ergs/sec, sufficient to provide for the flux of high energy cosmic rays.

These UHE data offered no conclusive evidence that the primaries of the observed showers were conventional gamma rays. The showers observed by Samorsky and Stamm from Cyg X-3[1] had a muon content comparable to that of ordinary cosmic ray showers. The Hercules X-1 burst events,observed by CYGNUS[13], also have a muon content that is anomalously large compared to that expected for gamma ray showers.

After six years of observations with more sensitive telescopes these questions have not been answered as no steady source of UHE radiation, conventional gamma rays or otherwise, has been observed with compelling statistical significance.

3 MILAGRO

Multi Institution Los Alamos,Gamma-Ray Detector

The field of gamma ray astronomy has been revolutionized by the CGRO and in particular by the EGRET instrument. EGRET has detected high energy gamma rays from about 2 dozen Active Galactic Nuclei(AGN) and from several Gamma Ray Bursters(GRBS). EGRET energy sensitivity extends to about 10 GeV. Many of the observed spectra are hard extending into the GeV range. It is, therefore of the utmost importance to extend the observation range beyond 10 GeV. Aperture limitations make this difficult for space based instruments. The MILAGRO instrument has been designed to explore the energy range above 100 GeV extending into the UHE range. The MILAGRO telescope will have the capability to observe over 1 sr of the the sky, continuously and be sensitive to a wide range of time scales.

3.1 Characteristics of MILAGRO telescope:

3.1.1 Layout

The telescope is based on the technique of using water cherenkov detector of large area, fully sensitive to all components (except neutrinos) of the air shower. Located at high altitude it can detect air showers with energy down to 100 GeV with good efficiency. The detector measures energy flow and samples a large number of particles in the shower front to minimize timing fluctuations. The detector is to use an already existing large covered pond , 60 m by 80 m and 8 m deep, located at Fenton Hill at an altitude of 8600 ft near Los Alamos. It will be instrumented with three layers of fast 8 inch phototubes. The Cherenkov light emitted by electrons and positrons, by pairs produced by photons in water, by muons traversing the detector and by hadrons making cascades will be detected by the layer of phototubes under 1.5 meters of water. A plan view of the Milagro water Cherenkov pond and associated air shower array is shown in Figure 3, also shown is a schematic of the cross section showing the placement of PMTs in the three layers.

3.1.2 Energy sensitivity and Trigger Efficiency

The energy sensitivity of MILAGRO detector is best illustrated by a plot of the effective area as a function of primary energy for three different trigger requirements for two different species of primary particles: protons and gammas. This is shown

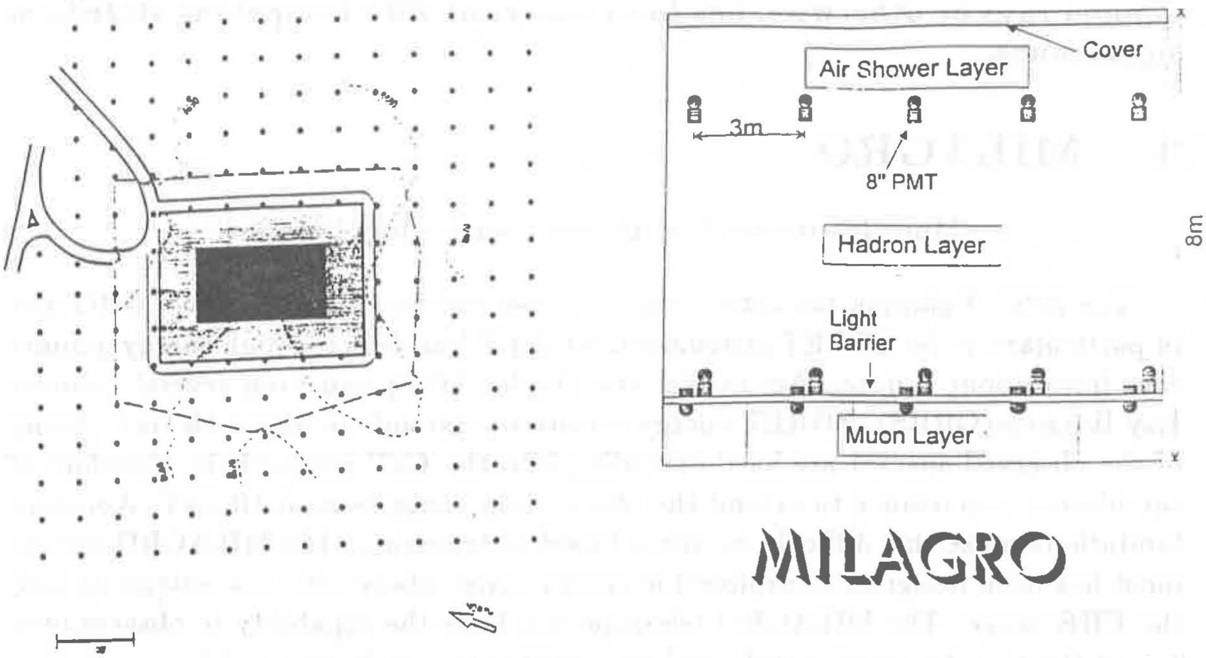

Figure 3: MILAGRO experiment at Fenton Hill. The dots are CYGNUS scintillators deployed around the Pond shown in the center.

in Figure 4. With a trigger requirement of 15 tubes the trigger rate is expected to be about 3 KHz. These curves also show a very important feature of MILAGRO at lower energies: **The trigger efficiency for low energy protons is at least an order of magnitude smaller than that for gamma rays at energies below 300 GeV.**

3.1.3 Angular resolution

The arrival direction is determined by timing. Because of the large number of particles detected per shower, the angular resolution will be $\leq 0.4°$ at 10 TeV, a considerable improvement over present values. Expected angular resolution based upon measurements made with the five pools in CYGNUS array is shown in Figure 5. For large showers (large number of PMT hits) the angular resolution improves to 0.25°.

3.1.4 Muon and Hadron detection:

A second layer of phototubes, looking upwards, will be sensitive to not only tails of electromagnetic showers but also to hadrons of high energy near the cores of air showers produced by cosmic ray nuclear primaries. A third layer of PMTs, near the bottom of the reservoir, will count muons in the shower. These tubes are shielded

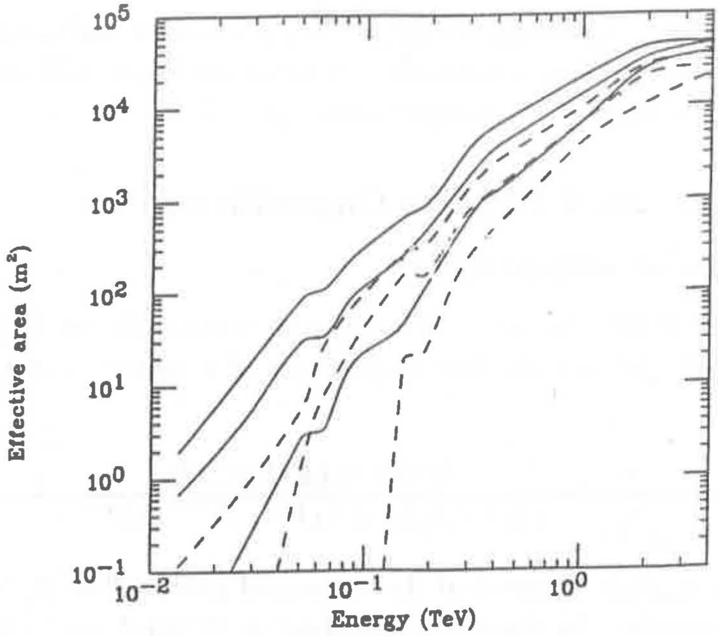

Figure 4: Effectvie area of MILAGRO as a function of primary energy. Dashed curves correspond to proton primaries and solid curves to gamma primaries. Three sets are for three different conditions. Lowest for greater or equal to 50 PMT, next for 25 PMT and topmost for 15 PMTs, respectively.

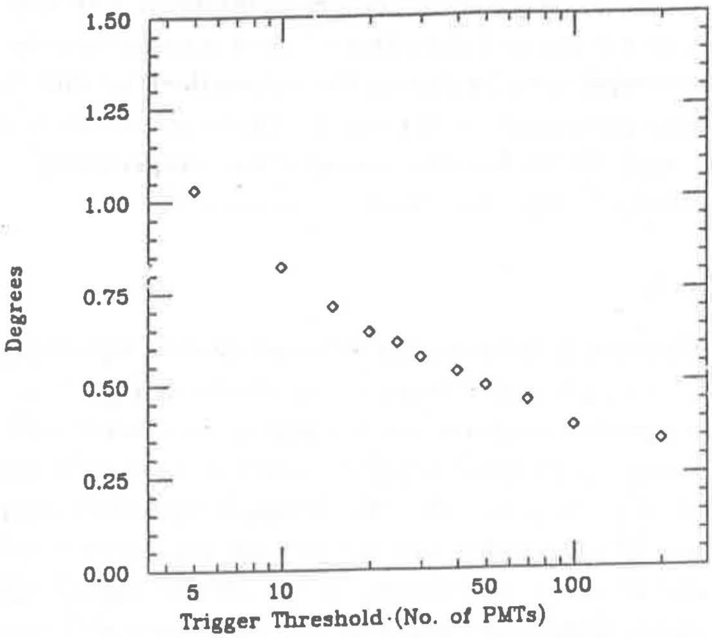

Figure 5: Expected angular resolution a function of illuminated photomultiplier tubes.

from downward coming Cherenkov light by opaque barrier and each tube will have its own 3mx3mx1m diffusing muon cell. The muon layer will provide excellent rejection of hadronic showers at energies above few TeV.

3.2 Sensitivity and Physics Capabilities

3.2.1 Point Source Sensitivity:

The ability of MILAGRO to detect a point source depends on both the intensity and the spectrum of the source. The significance of a signal from a source is given by

$$\frac{S}{\sqrt{(B)}} = \frac{0.72 \int A_\gamma(E) I(E) dE}{(\Omega T \int A_p(E) 0.1 (E_{TeV})^{-2.67} dE)^{0.5}} \tag{1}$$

where we have explicitly inserted the measured proton flux (5.1×10^{-2} m^{-2} s^{-1} sr^{-1}) in the denominator. In the above equation $A_\gamma(E)$ and $A_p(E)$ are the effective areas of the detectors for gamma rays and protons as a function of primary energy, Ω is the solid angle of the source bin, and I(E) is the source spectrum. The factor 0.72 is the fraction of source events that fall within the optimal angular bin and T is the observation time on the source. Background rejection of cosmic ray showers by muon detection can bye included in the effective areas.

There are two classes of constant sources of interest. The first is a source with a simple power law spectrum and the other class of sources are those with a cutoff in their spectra. The cutoff may be due to the source itself or due to the absorption of gamma rays as they propagate to the earth. Crab can be taken as a representative of the first class and AGNs for the second class, respectively. We discuss, next, MILAGRO sensitivity to the two classes of sources.

3.2.2 The Crab

MILAGRO can distinguish between the different spectra reported by the Air Cherenkov telescope groups, Whipple and Themistocle, shown in Figure 2. If the emission is steady, and if the spectra continue unchanged up to several TeV, then in one year of operation and using a 25 tube trigger condition we should observe 25 σ for the Themistocle spectrum, 11 σ for the Old Whipple spectrum and 7 σ for the New Whipple spectrum. These numbers do not include any rejection of hadronic showers based upon muons or other techniques. If we see the signal without muon rejection and if the signal disappears when we cut on events with muons then it would indicate onset of some significant new physics.

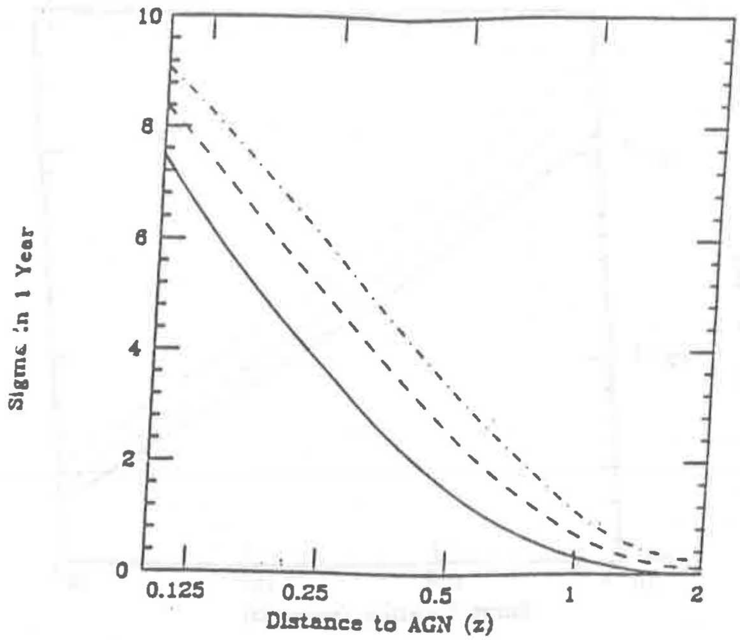

Figure 6: Expected Statistical significance of a signal from an AGN after 1 year of observation versus distance to the AGN

3.2.3 Active Galactic Nuclei

From Figure 1 it is clear that low energy threshold is needed to detect distance sources. In Figure 6 is shown the expected statistical significance of a signal from an AGN in MILAGRO after 1 year of observation versus distance to the AGN. The three curves correspond to the three different trigger requirments of Figure 4. The dot-dash curve is for a 15 PMT trigger, the dashed curve for a 25 PMT trigger and the solid curve for a 50 PMT trigger. The source flux used was 3.6×10^{-11}/E cm^{-2}, s^{-1},TeV^{-1} where E is in TeV. This roughly five times the flux of Mrk 421 and more typical of the observed AGNs by EGRET. A model for the extra-galactic IR field is used. The effect of a lower trigger threshold trigger is dramatic, MILAGRO with 15 tube trigger can see nearly twice as far as with a 50 PMT trigger.

3.2.4 Sensitivity to Gamma Ray Transients

MILAGRO has very good sensitivity for transients such as those from GRBs or evaporation Primordial Black Holes(PBHs) over a range of time scales from 100 ms to 100 seconds. Assuming a differential spectral index of -2.5(i.e. $A_0(E(TeV))^{-2.5}$), Figure 8 shows the sensitivity of MILAGRO as a function of duration of the burst. The y-axis is the differential burst flux (A_0 above), that yields a pre-trial probability of 10^{-8}. This guarantees a significant detection after any trial penalties are assessed

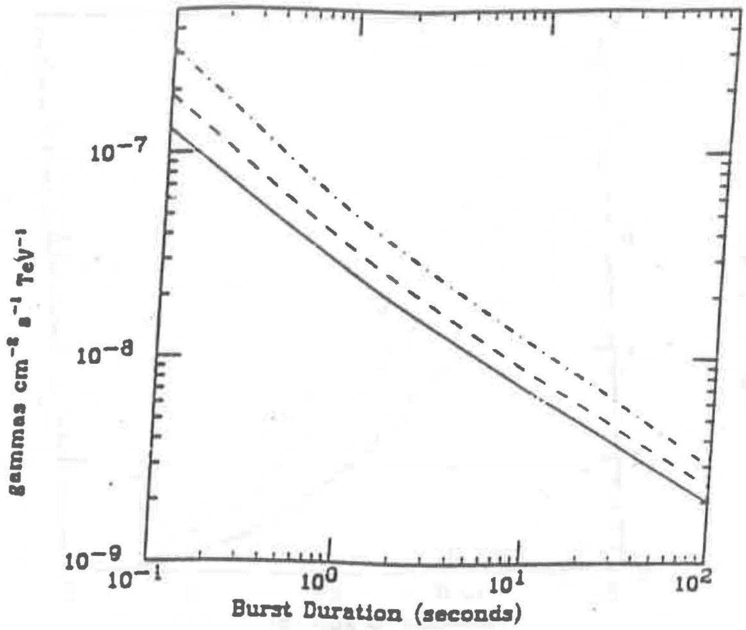

Figure 7: Sensitivity of MILAGRO as a function of burst duration

(because of poorly determined burst location, the examination of a number of bursts, etc.) For PBHs we present the sensitivity in another way in Figure 9 which shows the maximum distance to an observable evaporating black hole as a function of the zenith angle of the hole. The improvement over the sensitivity of the CYGNUS experiment is also shown.

3.3 Concluding remarks:

We expect the MILAGRO telescope to become operational by end of 1997. With the operation of the MIlAGRO instrument we will enter a new era in the study of high energy gamma sources such as AGNs, GRBs and other point sources, opening up a new energy range and providing continuous coverage of the overhead sky.

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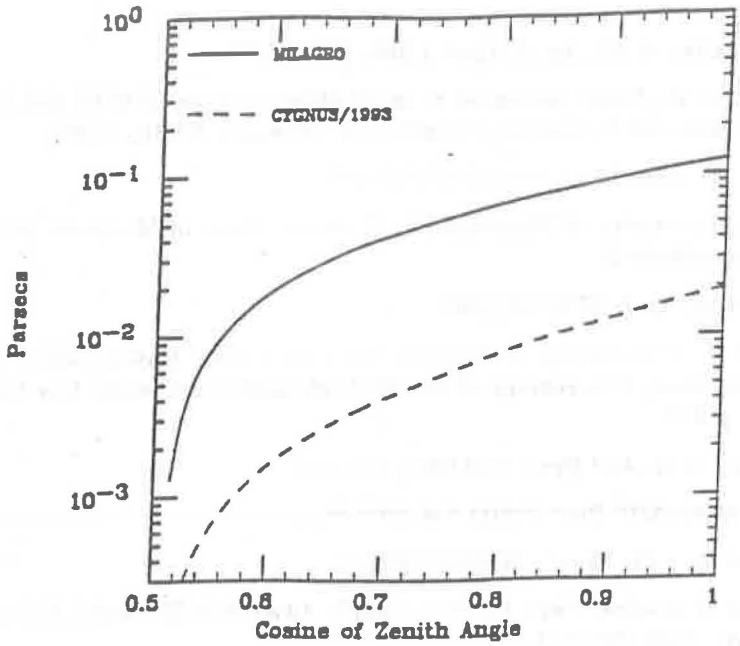

Figure 8: Distance to an observable evaporating PBH as a function of zenith angle of the PBH for MILAGRO as compared to that for CYGNUS

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