Particle Astrophysics with Milagro

1 Introduction

Particle Astrophysics is a new, exciting and rich field that explores topics that include the most energetic objects in the Universe, gamma-ray bursts, and the smallest, massive neutrinos. The Particle Astrophysics group at the University of Maryland has been actively involved in experiments that span this diverse field, Super-Kamiokande and Milagro. Milagro is a new type of detector that has just begun operation. It for the first time allows us to monitor a significant fraction of the northern sky at TeV energies on a 24-hour, 7-day per week basis. Our prototype detector, Milagrito, has produced results on the outburst of the Active Galactic Nucleus (AGN) Mrk501 and given tantalizing evidence for TeV emission associated with a gamma-ray burst.

Maryland has played a leadership role in the design and construction of the Milagro detector. The principal investigator, Jordan Goodman, is the co-spokesman for the experiment. This proposal requests support so that the Maryland group can continue our work on Milagro. It will allow us to continue to manage the experiment, plus play an active role the data analysis (including maintaining the archival database for the collaboration), as well as to help operate the detector. In this proposal we will describe the physics we will do with the Milagro detector, give a short technical description of the detector, and present physics results from our prototype detector, Milagrito. We will also briefly describe our plan for the addition of outrigger counters to complete the Milagro detector.

2 Physics with Milagro

High-energy gamma-ray astronomy uniquely probes non-thermal, energetic acceleration processes in the Universe. The list of known gamma-ray sources includes active galaxies, supernova remnants, and gamma ray bursts (GRB). Gamma rays are also produced when high-energy cosmic rays interact with matter in our galaxy. Other potential sources include more esoteric objects such as evaporating primordial black holes, topological defects, and dark matter particle annihilation and decay. Reviews of the techniques, science, and recent results in high-energy gamma-ray astronomy are available [1,2].

Cosmic gamma rays up to a few GeV can be directly detected with satellite-based detectors, such as EGRET [3]. EGRET has given us a new view of the sky at high energies. Among the many important discoveries was the discovery of a new class of extra-galactic objects, high-energy gamma-ray blazers (AGN) that emit a significant fraction of their energy at gamma-ray energies. At least two of these objects were later observed at TeV energies using ground-based air-Cherenkov telescopes. In addition, EGRET made coincident measurements of GRBs with the BATSE instrument also on the Compton Observatory. These measurements showed that GRBs emit gamma-rays with energies as high as tens of GeV.

At higher energies, the gamma-ray flux from even the brightest source is too low to be measured in the relatively small detectors that can be placed in satellites: thus earth-based techniques are used. High-energy gamma rays interact high in the atmosphere producing a cascade of particles called an extensive air shower (EAS). Ground-based gamma-ray telescopes detect the products of an EAS that survive to ground level, either the Cherenkov light produced in the atmosphere by the shower particles (by atmospheric Cherenkov telescopes [ACTs]) or the shower particles that reach ground level (by extensive air-shower arrays [EAS-arrays]).

After many years of perfecting the technique, ACTs have been successfully employed in the very-high-energy (VHE) region from ~ 300 GeV – 10 TeV to detect emission from several sources including three Plerions, three active galaxies, and one supernova remnant. These observations have greatly improved our understanding of the acceleration mechanisms at work in these sources.

The excellent angular resolution and sensitivity of ACTs make them ideal to study steady VHE emission as well as short-term flaring from known sources. However, ACTs can only be used on clear, dark nights, and can only view one source at a time (and only during that part of the year when that source is in the night sky). Thus they are not well suited to perform an all-sky survey, to monitor a known source for episodic emission, or to search for emission from a source at an unknown direction (such as from a GRB). On the other hand, an EAS-array can operate 24 hours per day, regardless of weather, and can observe the entire overhead sky; an EAS-array is able to observe every source in its field of view every day of the year. Previous EAS arrays have been sensitive to showers above 10's of TeV while Milagro is the first EAS detector which is sensitive below 1 TeV.

3 Scientific Goals of Milagro

Milagro will perform high-duty-factor, all-sky observations in the VHE region. We propose to use the Milagro detector to:

- Perform the first survey of the Northern sky for steady and episodic sources.
- Perform the first sensitive search for emission from GRBs for energies from ~100 GeV to many TeV.
- Detect VHE emission from the Crab and study its energy spectrum with a new, independent technique.
- Perform the first all-year monitoring of TeV emission from the known flaring sources Markarian 421 and Markarian 501.
- Search for emission from the galactic plane.
- Detect the shadow on the moon with high significance and use it to calibrate the energy response of the detector and to perform a search for high-energy cosmic antiprotons.
- Detect the shadow of the sun with high significance and use it to continuously monitor the strength of the transverse component of the solar magnetic field.
- Perform the most sensitive search for evaporating primordial black holes.
- Search for solar coronal mass ejections in an unprecedented energy regime over unprecedented time scales.

3.1 Active Galactic Nuclei

In the current model of active galactic nuclei (AGN), the central engine contains a super-massive black hole of mass ~ 10^7 - 10^{10} solar masses. There is a thin accretion disk around the hole, surrounded by a thick torus lying in the equatorial plane of the hole. In addition, radio-loud AGN have well-collimated jets perpendicular to the accretion disk. In this model the central engine is powered by accretion --- the change in gravitational potential energy of in-falling matter. This is a very efficient process that may convert as much as 10% of the rest mass of the accreted matter into radiation.

Active galaxies emit radiation over the entire electromagnetic spectrum from radio waves to TeV gamma rays. Thermal emission emanates from the accretion disk (infrared to X-rays) and the torus (infrared). Non-thermal emission (radio and gamma-rays) comes from the jets. One of the more exciting discoveries of the 1990s has been the observation of TeV emission from several AGNs. TeV emission has been observed from Markarian 421, Markarian 501, and 1ES2344+514. Markarian 501 and 1ES2344+514 are the first gamma-ray sources discovered by ground-based instruments: they are not bright sources of photons for EGRET. The TeV observations are characterized by great variability on time scales ranging from years to tens of minutes. Mrk 501, a seemingly weak and barely detectable source (1995) later became the brightest gamma-ray object in the sky (1997). Unfortunately, a source such as this can be observed by ACTs no more than ~12 nights/month due to clouds and the bright moon and only over roughly one-half of the year as the source is unobservable when it rises and sets in daylight. The three AGNs observed to emit TeV photons are all relatively nearby ($z<0.05$) BL Lacs, a subclass of AGN types believed to have a jet pointed towards the observer. The fact that they are relatively close may be due to the absorption of the VHE photons by the process $\gamma\gamma \rightarrow e^+ e^-$, where the VHE photon scatters off intergalactic infrared photons. While the physics of this process is well understood, the strength of the intergalactic IR field is not. Present measurements only give an upper limit on the IR strength.

The astrophysics of the gamma-ray emission from AGN jets is best explored using multi-wavelength observations. Several such multi-wavelength observations have been made of Markarian 421 and Markarian 501 while they were flaring. Their spectra show a characteristic two-hump structure that is usually explained in terms of the synchrotron self-Compton model, with the lower energy peak due to synchrotron emission from relativistic electrons and the high-energy peak due to due to the Compton scattering of the synchrotron photons by the same high-energy electrons. However, the observations cannot yet distinguish between models in which the particles accelerated in the jet are electrons or protons.

Milagro will uniquely contribute to our understanding of TeV blazars in several ways:

- Milagro will survey the entire northern sky every day for TeV emission from all blazars.
- Milagro will monitor the TeV activity from the known TeV blazars every day and alert ACTs of evidence of activity for detailed, follow-up study.
- Milagro will obtain an independent measurement of the VHE flux and energy spectrum from known TeV blazars.

3.2 Supernova Remnants

The Crab nebula was the first detected source of TeV photons and remains the standard candle for VHE observations in the northern hemisphere. Milagro will detect VHE emission from the Crab with high significance ($>5\sigma$) in a few months. The signal from the Crab will be used to determine the resolution and sensitivity of Milagro to photons, and to optimize analysis techniques including algorithms to distinguish photon-initiated showers from showers produced by background cosmic rays.

SNRs are believed to be the source of the hadronic cosmic rays observed in the solar system up to ~100 -1000 TeV and inferred from observations of high-energy photon emission to be present throughout the Galaxy. There is, however, no conclusive evidence that this is so. The hadronic cosmic rays bend in the interstellar magnetic fields and so they do not point back to their source. The process that accelerates hadrons should also accelerate electrons and so generate photons via synchrotron radiation and bremsstrahlung. EGRET may have detected gamma rays from several Galactic SNRs, but its poor angular resolution and the large gamma-ray background in the Galactic plane makes positive identification difficult. However, the accelerated hadrons should give rise to high-energy photons from the decay of neutral pions produced in their interaction with nearby matter: these high-energy photons would point back to the SNR and provide definitive evidence of their role in cosmic ray acceleration.

Upper limits on the TeV and PeV gamma-ray flux from SNRs presumably observed by EGRET are not sufficiently sensitive to rule out the picture of SNRs being the source of cosmic rays, although they do rule out part of the allowed parameter space (Gaisser, Protheroe, Stanev, 1998). More sensitive TeV measurements should settle the issue.

Milagro will advance our understanding of SNRs and their role in role in cosmic-ray acceleration. Milagro will observe all SNRs in the northern sky every day and significantly improve the sensitivity for TeV emission compared to the measurements by Whipple, which are based on observations lasting less than 15 hours. Milagro's sensitivity is not reduced by the presence of a nearby bright star, by the bright optical background in the Galactic plane, or by the fact that an SNR may be an extended source.

3.3 Gamma Ray Bursts

The origin of gamma-ray bursts (GRBs) is arguably the most interesting puzzle in astrophysics. Observationally, GRBs are short-duration (1 ms to tens of seconds or longer) bursts of gamma-rays that come from apparently random locations in the sky. Observations by the BATSE instrument on the Compton Gamma Ray Observatory [Meegan *et al.*, 1996] show that the bursts are isotropically distributed and have an underabundance of low-fluence bursts, indicating that we are seeing to the edge of the source distribution. These observations are consistent with a cosmological origin for GRBs. More recently, several optical and radio counterparts have been detected and demonstrate the cosmological origin of GRBs [Andersen *et al*., 1999]. GRB 990123 was particularly extensively studied. This burst is seen to be in a host galaxy at z = 1.6. Currently favored cosmological parameters imply that an isotropic energy release equivalent to the rest mass of 1.8 neutron stars (4.5×10^{54} erg) was emitted in gamma rays, assuming isotropic emission of gamma rays.

EGRET has observed photons from GRBs up to ~20 GeV with no evidence of a spectral turn-over at high energies. The observed spectra are power laws with differential indices of 1.95 ± 0.25 [Dingus, 1998]. The detection of TeV photons from a GRB would have a major impact on emission models, especially on the bulk Lorentz motion in the source. Detection of gamma rays above ~1 TeV would probably constrain the redshift to z ~ 0.5 due to absorption of the photons by the intergalactic IR field (if current models of IR are correct).

Milagro is the only instrument capable of detecting gamma rays before, during and after a GRB at energies ~200 GeV and above: the Milagro scalers are sensitive to photons below 100 GeV.

3.4 Galactic Plane

Diffuse Emission from the galactic plane is the dominant source in the gamma-ray sky (Hunter 1997). The origin of very-high-energy diffuse emission was conventionally understood to be due to the decay of π^0s produced by the scattering of cosmic-ray hadrons off interstellar matter. The flux of gamma-rays measured by EGRET below 1 GeV fits models well, while between 1 and 100 GeV models predict fluxes 60% less than the measured. It has been suggested (Porter 1997) that the enhanced emission at high energies is due to inverse-Compton scattering from cosmic-ray electrons. A candidate source for very-high-energy elecrons is supernova remnants, where X-ray observations of synchotron radiation indicate the presence of electrons above 30 TeV (Pohl 1998). If cosmic-ray electron cooling and not hadronic interactions is the dominant source of diffuce gamma-ray emission from the galactic plane then, the flux might well be as much an order of magnitude higher than previously thought. For this reason, ACTs have been spending an increasing amount of time searching for TeV gamma-rays from the galactic plane (Lampeit 1999, LeBohec 1999). Milagro, because of its large apperature and high duty cycle, is the worlds most sensitive instrument for the detection of diffuse emission above 1 TeV.

3.5 Exotic Phenomena

Black holes radiate a nearly thermal spectrum, where the effective temperature is related to its mass by $T = (10^{13}/M)$ GeV, where M is in grams. As with any gravitationally bound system the specific heat of a black hole is negative: the more energy it loses, the hotter it gets. The luminosity of a black hole increases with the square of the temperature [Thorne *et al*, 1986] and is proportional to the number of available states (elementary particles) for the radiation, which increases with the temperature of the black hole. Thus the radiation is a runaway process that leads to the complete evaporation of the black hole with a rather spectacular end. The black holes of interest here have very small masses (holes with a mass of ~10^{14} grams at the Big Bang would be evaporating now). These primordial black holes would be formed by density fluctuations in the early Universe on very small mass scales.

A detector of TeV gamma rays is well suited to search for the evaporation of a black hole. At lower energies the luminosity is low, the background is high, and there is no unique time signature. At higher energies too little total energy is released to be observable. Milagro is the most sensitive instrument to search for the evaporation of primordial black holes.

4 Milagro Technical Description

The goal of the Milagro project is to build a detector sensitive to cosmic gamma rays around 1 TeV while maintaining the all-sky, high duty-factor capabilities of an EAS-array. A typical EAS-array has scintillation counters covering <1% of the total area of the array. Thus, at best, only a small fraction of the shower particles surviving to ground level are detected, which results in a high energy threshold. This is compounded by the fact that showers at ground level contain many more photons than charged particles and scintillation counters do not detect photons with high efficiency.

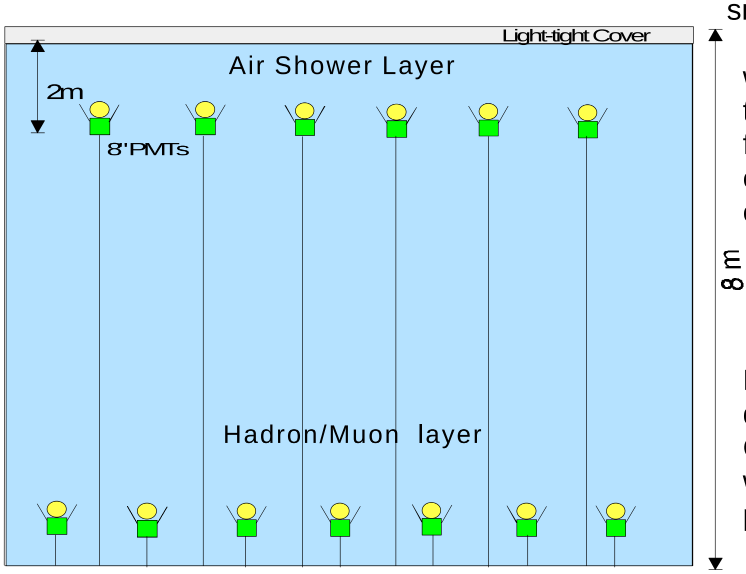


Figure 1 – Milagro layout

Milagro uses photomultiplier tubes deployed under water to detect the Cherenkov radiation produced in the water by relativistic charged shower particles. Because water is inexpensive and the Cherenkov cone spreads out the light, one is able to construct a large instrument that can detect nearly every charged shower particle falling within its area. Furthermore, the plentiful photons convert to electron-positron pairs (or a electrons via Compton scattering) that, in turn, produce Cherenkov radiation that can be detected. Consequently, Milagro has an unprecedented low energy threshold for an EAS-array.

As in a conventional EAS-array, the direction of the primary gamma ray is reconstructed in Milagro by measuring the relative times at which the individual PMTs are struck by the light produced by particles in the shower front.

Figure 2 Milagro Pond during filling

The amount of water above the PMTs should be large enough for nearly all of the photons to convert into electrons and positrons, but not so thick that the light produced at the top is absorbed before it reaches the PMT. As the depth of water above the PMTs increases, the width of the observed timing distributions increases. This is caused by two effects: the difference in the arrival time of Cherenkov light produced at the top of the layer and that produced by a pair created deep in the layer increases, and the geometrical area viewed by each PMT increases. Countering these effects is the increased sampling of the shower as the water above the PMTs increases. The optimal water thickness depends on the angular resolution and the energy threshold, both of which are affected by the water depth. From Monte Carlo simulations one expects the optimal depth to be a 1-2 meters. Our prototype detector Milagrito demonstrated that a 1.5m would be optimal.

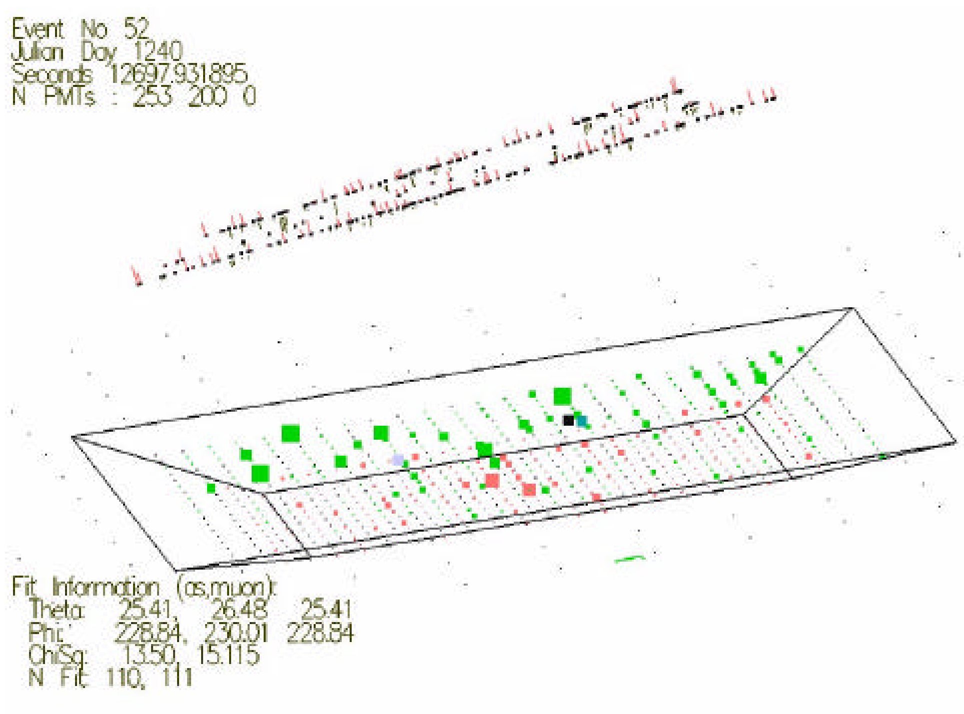
4.1 The Hardware

The heart of the Milagro detector is the array of 450 photomultiplier tubes deployed under 1.5-m of water to detect air-shower particles reaching the ground. These PMTs measure the arrival time and density of the air-shower particles. In addition, 273 PMTs are located at the bottom of the pond under ~7 m of water and are used to distinguish photon-induced showers from hadron-induced showers. The top array of PMTs is called the shower layer and the bottom array is the muon layer.

Milagro uses 20-cm-diameter Hamamatsu 10-stage R5912SEL PMTs with good resolution for single-photoelectron pulses. Custom-made front-end electronics boards provide timing and pulse height information for each PMT channel. The pulse height is measured using the time-over-threshold (TOT) technique. The dual requirements of good timing information independent of PMT prepulsing and a large dynamic range on the pulse height measurement led to a dual-threshold system. Both timing and TOT information are recorded for two different discriminator thresholds; low threshold (~1/4 PE) and high threshold (~5PE). The front-end boards also provide triggering monitoring information. The Milagro uses a simple multiplicity trigger.

The timing and pulse height information is encoded as a series of TDC edges, digitized in three LeCroy 1887 FASTBUS TDC modules. After digitization the data is readout with a FASTBUS Smart Crate Controller (FSCC), which transfers the data to a pair of dual-ported VME memory modules via a smart controller. This controller writes the data into the memory boards on the VSB bus. A Silicon Graphics (SGI) Challenge L multi-CPU computer reads the data from the memory boards over the VME bus. The use of two memory boards allows for the simultaneous reading and writing of data. Milagro operates at a trigger rate of ~1 kHz with less than 1% dead time. The data is then decoded, calibrated, and reconstructed in real time. The raw data is written to disk before being archived to DLT tape. This readout system was developed by a collaboration between the Maryland Group and Fermilab.

The experiment is controlled by commands issued from the SGI computer. The computer communicates with the FSCC via the ethernet port on the FSCC. From the SGI one can initialize the FASTBUS modules and prepare the system for data taking. The online system monitors error rates and resets the FASTBUS system as necessary. When human intervention is required, an alert is sent and the physicist on shift receives a pager message. The system can be monitored and controlled remotely via the web. The event processing is performed on line by several semi-autonomous routines.



Fgure 13 - Air Shower event in Milagro. The two lines are the timing fits from the EAS (lower line) and Hadron (upper line) layers. The green (red)squares are proportional in size to the signal in the EAS (muon) layer.

4.2 Milagro Performance

The construction of the Milagro detector was completed in the winter of 1998/99 and operations began in early 1999. Figure 4 shows the trigger rate for Milagro as a function of the number of PMTs required for a trigger. Above 50 PMTs the rate falls off due to the increase in shower energy required to trigger and thus gives a an undesirable increase in energy threshold. Below 50 PMTs the trigger rate increases rapidly and becomes dominated by non-shower events such as single muons. The figure indicates that the optimal threshold for triggering would be about 50 PMTs giving a ~2 kHz trigger rate. Figure 5 shows the trigger rate versus day of the year for Milagro. In June the detector began operating at greater then 1 kHz and in August the detector was approaching a trigger rate of 2kHz before it became necessary to turn off for summer maintenance and repair of PMTs.

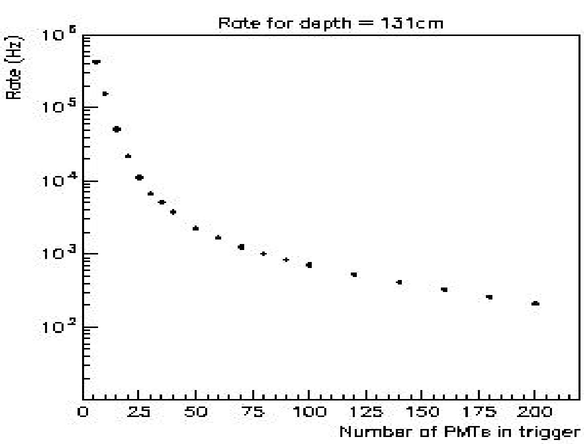


Figure 4 Trigger rate vs # of PMTs hit.

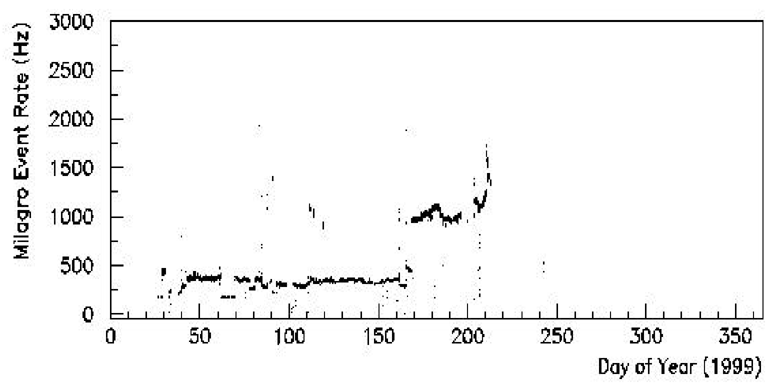


Figure 5 – Trigger rate vs day of 1999

A measure for the angular resolution of the Milagro detector can be found by looking at the "DELEO/2" distribution of figure 6. DELEO is the space angle difference between the fits using the "odd" and "even" tubes in the array and is approximately the angular uncertainty (excluding certain systematics). This shows that Milagro's angular resolution is about 0.35 degrees. The corresponding number for the prototype detector, Miligrito (triggering on the same showers), was about 0.9 degree. This significant improvement comes from the increased number of tubes, adding baffles to the tubes and going to a water depth of 1.5m. The improved angular resolution, increased sensitive area, and gamma-hadron separation makes Milagro a much more sensitive detector then its predecessor Miligrito.

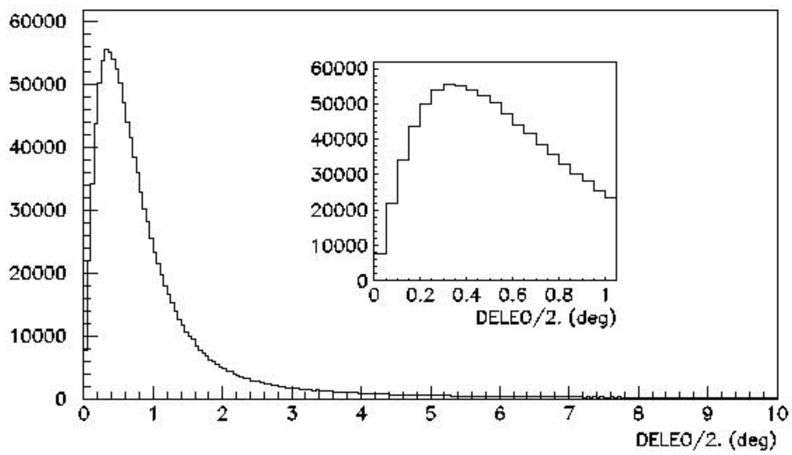


Figure 6 Distribution of "DELEO/2" for Milagro. The intrinsic angular resolution of the shower fit is giving by the peak of this distribution. This indicates that Milagro's intrinsic angular resolution is approximately 0.35 degrees.

4.3 Gamma/Hadron Separation

We have been studying how to reject hadron induced showers which are our background. These methods depend on the feature that gamma-ray induced showers are relatively smooth as a function of radial distance from the core while proton showers are 'clumpy' due to the presence of muons, high energy gammas and hadrons. In the air shower layer of Milagro their presence is obscured by the general illumination by shower particles but their presence can show up in the muon layer (bottom layer). The improvement in gamma-ray signal to noise from a source can be quantified by a Q factor, defined as the ratio of fraction of gammas retained divided by the square root of fraction of protons retained. Detailed simulations show that this Q-factor depends on core distance. For cores inside the pond Q-factors will be as large as 2 to 4. A Q factor of 3 corresponds to rejecting more than 90 percent of cosmic ray showers, while keeping 50 percent of the desired gammas. We plan to optimize methods to achieve this improvement and develop an optimal on-line algorithm to reject hadronic showers.

5 Proposed Research

5.1 Maryland's Role in Milagro

The Maryland group played a major role in the original proposal for Milagro and continued this role in design and construction phase of the detector. Maryland had specific responsibilities in the areas of project management, data acquisition (DAQ) and construction and will continue to have a major role in detector operations and data analysis now that the detector is operational.

The Maryland group designed and implemented the Fastbus/VME DAQ system that enables Milagro to take events at greater than 2 KHz with minimal deadtime. Currently, Maryland has developed a real-time water quality monitoring system which is being implemented at the Milagro site Maryland is also responsible for overall project management. Jordan Goodman is the co-spokesman for Milagro and was the P.I. for the construction grant. During construction he participated in all major design decisions, overseeing all contracting as well as taking part in the actual construction. *Milagro was built on time and on budget.* During the operations and data analysis phase of Milagro, the role of the spokesman shifts to overseeing the operating of the experiment and facilitating the various analysis efforts.

Maryland will have a full-time post-doc on site at Milagro and one at Maryland. In addition, a third post-doc will be stationed at Maryland, but will spend construction season (summer – fall) at Los Alamos. The onsite post-doc (Javier Bussons Gordo) will play a major role in calibrating the detector, maintaining the DAQ system, processing the data and doing online physics analysis. Andy Smith (post-doc), who was a major player in the development of the Milagro analysis and reconstruction software, will be at Maryland. He also the developed the experiment monitoring system at Milagro while he was employed by UCR. Andy and Xie Wei, who is joining our group as a post-doc, will work closely with the full-time faculty (Goodman and Sullivan), visiting faculty (Ellsworth and Berley), and graduate students on further development of analysis techniques and physics analysis. They will also maintain the database plus develop access tools for the entire collaboration to use in analysis. All personnel will participate in shift taking and detector operations at Los Alamos.

The Milagro detector gives us the opportunity to explore the very-high-energy sky with a new and unique instrument. The Maryland group will take an active role in analysis of Millagro data and operating the detector to accomplish the primary scientific goals of Milagro which were described in detail earlier.

5.2 Online Database

Milagro data is reconstructed online at the site. The output is recorded on DLT tape. There are several streams of data including source files and the sun and moon. The output of the reconstruction for all events is stored in a highly compressed form and will be the archival database for the experiment. The Maryland group will maintain the Milagro archival database for the collaboration at the University of Maryland. The database will be about 1.3Terabytes per year. It is now possible to keep this data on disk at a reasonable cost. With the cost of disk down to about $30/GB, the media costs are less than $40K per year. This database will let allow all members of the collaboration to do analysis on the entire data set. This database is vital to the productivity of the collaboration. Maryland is requesting the resources to store the data and provide the CPU power to do analysis on this data set. Other institutions can run analysis jobs on this data and extract and copy subsets to use at their own institutions. At this time the most cost effective way to store and store the data is RAID 5 units being served by LINUX PCs. We are also studying network RAID servers. Andy Smith who will be at Maryland is our group expert on these systems. The University of Maryland is providing high speed network connections to these computers – starting at 100mb/sec and being upgraded to gigabit speeds. This will make access easily available to the entire collaboration. We already have a 15 tape DLT drive at Maryland.

5.3 Outrigger Water Tank Array

The Milagro pond is the central part of the Milagro detector. With the pond alone we trigger on and accurately reconstruct very low energy showers that strike it. However, many showers trigger the Milagro detector even though their cores do not fall directly on the pond. It is vital to be able to determine the shower core position to substantially improve the performance of Milagro with respect to angular resolution, gamma-hadron separation and energy determination of each event. We hope to deploy this array in summer and fall of 2000 and 2001. An outrigger scintillator array was part of the initial proposal for Milagro. Since then we have shown that water tanks are more effective for the showers in the energy range we are studying. We want to complete the complement of water tanks to surround the Milagro pond to be able to determine core location of events which do not land on the pond. We have built and deployed 11 tanks around the pond in 1998 to study their performance and reliability over long times and have shown our design to be effective. In Figure 7, simulations show that outriggers significantly improve angular accuracy. The cost of the water tank array is included in the overall Milagro construction and operations proposal and is not a part of our budget in this proposal.

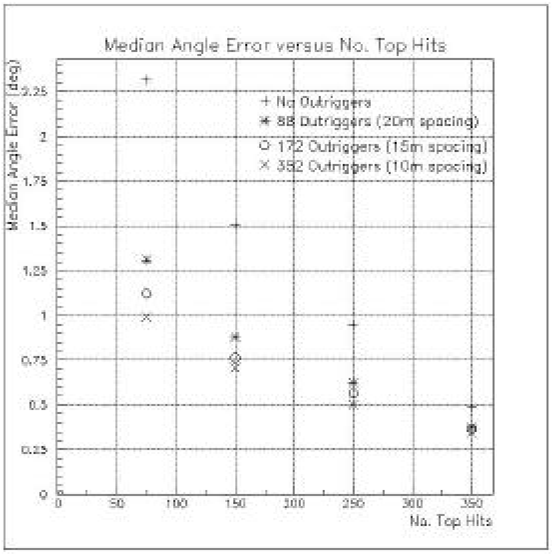


Figure 7 - Median angle error versus number of hits in the top layer for different outrigger arrangements

5.4 WACT

A Wide Angle Cherenkov Telescope array (WACT) is being constructed at the Milagro site. WACT will enhance Milagro performance as well as to determine the composition of primary cosmic rays extending over a region where direct measurements exist into the PeV region of the knee. (1) WACT will provide independent confirmation of the pointing accuaracy of MILAGRO, (2) it will provide an independent estimate of energies of events which are coincident with Milagro triggers. (3) Composition with WACT: Milagro is a very large muon detector. It will form a powerful instrument for determining the composition of cosmic rays in the energy range 20 TeV to a PeV, if complemented by an array of wide angle Cherenkov telescopes (WACT). In order to do composition studies it is important to know the energy of primaries triggering the pond. WACT has the capability of doing this using the lateral distribution of Cherenkov light. Simulations show that density of Cherenkov photons at about 100 m from the core of the shower (determined independently by the outrigger array) is a good measure of the primary energy, E, - almost independent of the primary mass. The ratio of Cherenkov densities at near 40 m from the core to that at 100 meters from the core can be related to the location of the maximum of the shower development in the atmosphere, X_{max}. X_{max} is a measure of the atomic mass of the primary as high Z showers start earlier than proton showers. Milagro response as quantified by ratio, R, of total photoelectrons in the bottom and top layers is also a measure of penetrating muons in the shower that also depend on the atomic mass of the primary. So the aim of this experiment would be to use E, Xmax and R to estimate the average mass of the primaries and assign a probability to each event what mass group the event belongs to. WACT will overlap the region near 1 TeV where there are direct measurements of the composition. The WACT experiment is under construction and will be finished in the spring of 2000.

6 Results from Previous Support

6.1 Milagrito

Milagrito was built as a prototype for Milagro. Milagrito was essentially a smaller version of the air-shower layer of Milagro with 228 photomultiplier tubes (PMTs) covered by between 1 and 2 meters of water. Although the primary purpose of building Milagrito was to test installation, operations, and analysis techniques and hardware for Milagro, it was a fully functioning detector in its own right and took data (nearly 9-billion events) from February 1997 to May 1998. These data have been analyzed and a brief review of the results obtained will be given here. Of course

Milagro, with a much larger air-shower layer, a muon/hadron layer with the ability to distinguish gamma-ray showers from hadron showers and an outrigger array to determine the core position, will have much better sensitivity than Milagrito. Simulations indicate that the expected signal from the Crab should only be ~1σ for the Milagrito data set.

6.2 Results from Milagrito

6.3 Markarian 501

The Milagrito data-taking period included the time when Markarian 501 was undergoing a long-lasting flare and was the brightest TeV object in the sky. Mrk 501 was intensively studied by a number of ACTs during this flare (Protheroe *et al*., 1997), and the energy spectrum has been measured by the Whipple group (Samuelson *et al*., 1999) and the HEGRA group (Aharonian *et al.*, 1999). Thus Mrk 501 is the ideal source to use to study Milagrito's response.

In Milagrito (and Milagro), a gamma-ray signal from a source appears as an excess of events from the source direction, compared with the isotropic background from cosmic-ray showers. According to simulations, a bin size of radius 0.9° (which contains ~57% of the events from a source) is optimal for an analysis that treats all Milagrito events equally; a more sophisticated analysis is underway that takes into account the dependency of the angular resolution with the number of PMTs participating in the event. Figure 8 shows the significance of the event excess in the vicinity of Mrk 501. At the source position, an excess of 2778 events with an estimated background of 498,752 events is observed, corresponding to a significance of 3.7 σ. We interpret this result as a confirmation of Mrk501 as a TeV gamma-ray source and the first source detection by an EAS array.

Using the average flux measured between February and October 1997 (JD 50490 - 50721) by the Whipple and HEGRA groups, simulations predict an event rate of (9.5 ± 2.9) events/day, which is consistent with the rate measured by Milagrito during this period of (10.5 ± 3.5) events/day.
This result has been accepted for publication in AP. J. Letters (Ref).

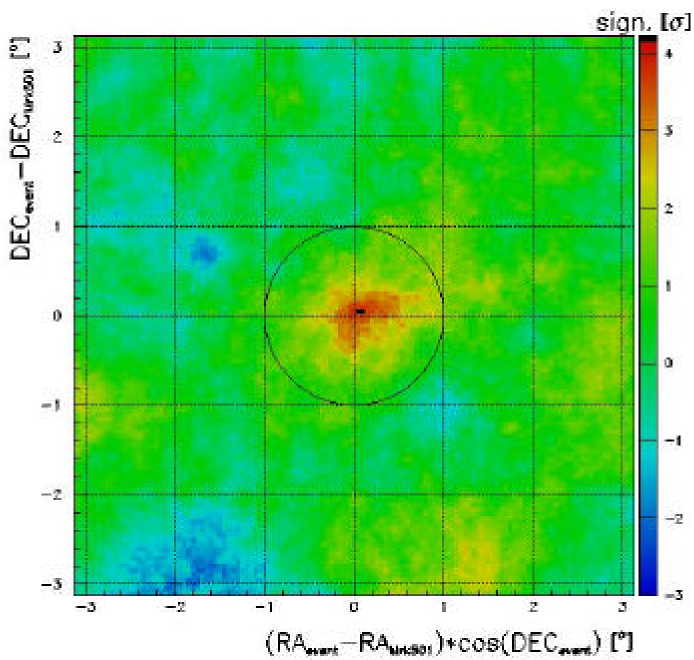


Figure 8 Significance of the excess of events in the region of Mrk 501 from Milagrito data.

6.4 Gamma-Ray Bursts

During the lifetime of Milagrito, 54 gamma-ray bursts detected by BATSE were within 45° of zenith. The Milagrito data set was analyzed to look for evidence of VHE emission coincident with the time and location of the BATSE burst (Leonore *et al*, 1999). The search time used was T90, the time during which BATSE reported detecting from 5% to 95% of the total counts for each GRB; for the 54 bursts, T90 ranged from hundreds of milliseconds to 200 seconds. A search bin with a radius equal to the 2σ confidence radius reported by BATSE for each GRB. The search area was examined with a grid of overlapping bins on the celestial sphere of size appropriate to optimize the significance of a signal from a point source which for our resolution is 1.6°. In order to establish the significance of a detection, the background due to cosmic ray induced showers must be estimated and statistical and non-statistical fluctuations must be understood. The angular distribution of background events on the sky was characterized using two hours of data surrounding each burst. This distribution was then normalized to the number of events detected by Milagrito over the entire sky during the time period of interest. The Poisson probability that the number of events in each bin was due to a background fluctuation was calculated and the bin with lowest probability was then taken as the candidate position of a TeV gamma-ray counterpart to the BATSE burst. The true probability of obtaining the observed significance within the entire search region was determined by Monte Carlo simulations. For each burst a set of 'fake' signal maps were obtained by randomly drawing N T90 events from the background distribution.

The data were searched, as before, for a significant excess within the search region defined by BATSE. The true probability after accounting for the size of the search region is given by the ratio of the number of simulated datasets with probability less that that observed for the actual data to the total number of simulated datasets. One of the 54 bursts, GRB 970417a, shows a large excess above background in the Milagrito data. The BATSE detection of this burst shows a typical weak burst and T90 of 7.9 seconds. The low BATSE flux results in a BATSE determined position with a large 1σ statistical uncertainty of ~6°. The bin with the largest excess in the Milagrito data is 3.8° away from the BATSE determined position. Figure 9 shows the number of counts in this search region for the array of 1.6° bins. The bin with the largest excess has 18 events with an expected background of 3.46 events. The Poisson probability for observing a signal this large due to a background fluctuation is 2.89×10^{-8} . The probability of such a detection within the entire 9.4° search region for this burst determined by Monte Carlo simulation was found to be 2.4×10^{-5} . Because 54 bursts were examined, the probability that is was a background fluctuation was in any burst is 1.5×10^{-3} . Although the initial search was limited to T90, for GRB 970417a longer time intervals were examined. EGRET observed longer duration GeV emission, and TeV afterglows are predicted by several models. To allow for the positional uncertainty of the TeV γ-ray detection during T90, the radius of the

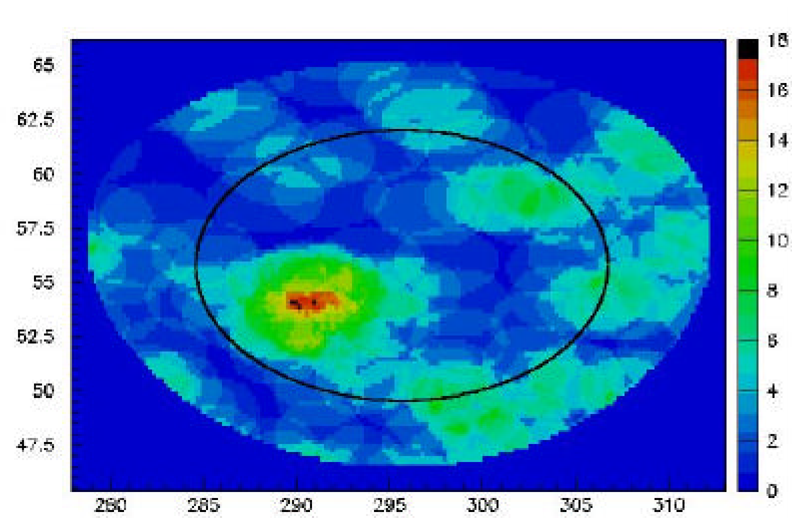


Figure 9- GRB 970417a - Number of events in a 1.6° bin. Maximum is 18 events with a background of 3.46

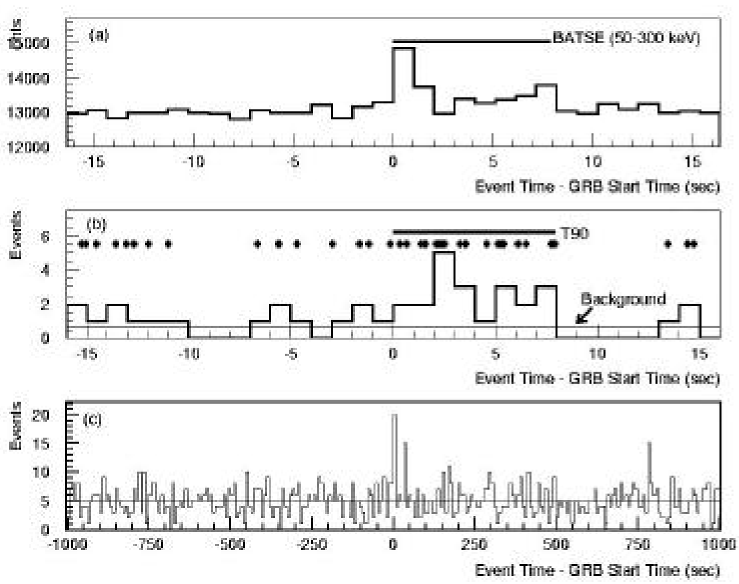


Figure 10 (a) The BATSE signal (b) Milargito signal (c) Milagrito expanded time window

search bin was increased to 2°. A search for TeV γ-rays integrated over long time intervals of one hour, two hours and a day after the GRB start time did not show any significant excess. Lightcurves of shorter time interval searches where the data are binned in intervals of one second and of T90 (7.9 secs) are shown in figure 10. In addition to the excess of events observed at 0 secs for T90, the two most significant features can be seen starting 32 secs and 782 secs respectively after the γ-ray burst start time. In both cases 15 events were observed with an expected background level of 5.4 events. Milagrito does not have the capability to reject hadron background, but Milagro will. In addition the outrigger array will give us the capability to determine shower energy with much better accuracy. In addition, Milagro's lower threshold would have given us ~180 signal events for this burst.

This result was presented at the 26th ICRC in Salt Lake and at the TeV workshop in Snowbird. An Ap.J. Letter is being submitted.

6.5 A Ground-Level Event from a Solar Coronal Mass Ejection

While particle acceleration beyond 1 GeV at the Sun is well established, few data exist for protons or ions beyond 10 GeV. The energy upper limit of solar particle acceleration is unknown but is an important parameter, since it relates not only to the nature of the acceleration process, itself not ascertained, but also to the environment at or near the Sun where the acceleration takes place.

On 6 November 1997 at approximately 12:00 UT, an X-class flare with an associated coronal mass ejection occurred on the Sun. This produced a nearly isotropic ground level event registered by many neutron monitors. Climax, located in nearby central Colorado, is the closest of these neutron monitors to Milagrito. Milagrito registered a scaler rate increase coincident, within error, with that measured by Climax (see Figure 11) (Ryan et al. 1999). If one accounts for the meteorological fluctuations, the event duration and time of maximum intensity, as seen by Milagrito, are also consistent with that of Climax. This detection indicates the presence of >10 GeV particles. There is also evidence for an increase in the trigger rate at the same time. This increase can be caused by high energy primaries (> 100 GeV) or by secondary muons arriving from a nearly horizontal direction. Further analysis is underway to distinguish these components and to derive an energy spectrum from the Milagrito.

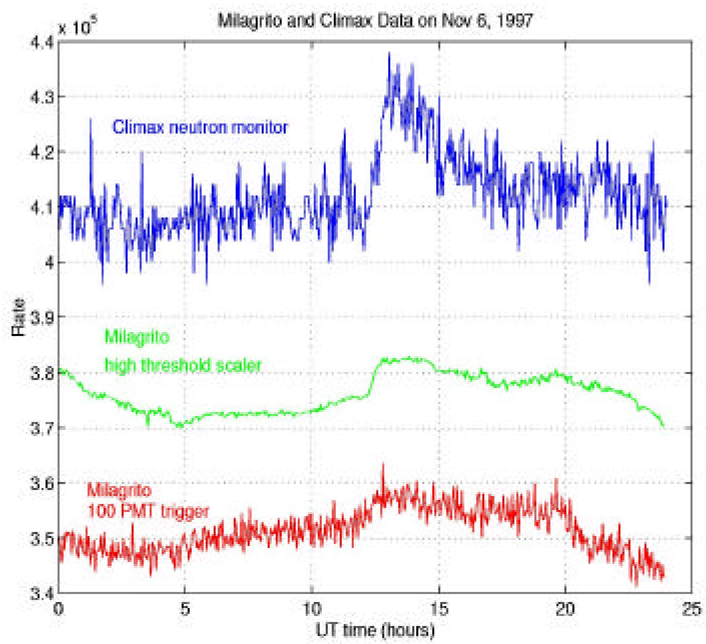


Figure 11 The Milagrito scaler rate and 100 PMT trigger rate on Nove 6, 1997

This result was presented at the 26th ICRC in Salt Lake and a publication is in preparation.

7 Particle Astrophysics at Maryland

7.1 Super-Kamiokande

Both Professors Sullivan and Goodman have played important roles in the Super-Kamiokande experiment. The results from Super-K on neutrino oscillations and neutrino mass have been some of the most exciting in recent years (refs). While both faculty members participate in both experiments, Greg Sullivan heads the Maryland effort on Super-K and Jordan Goodman heads the Milagro effort. Maryland has been actively involved in Super-K from the beginning of the experiment. Among other things, Maryland developed the outer detector DAQ for Super-K (which is very similar to Milagro's DAQ) and graduated the first student from the experiment, Zoa Conner. Recently, Sullivan is leading an effort that has developed and deployed a new type of calibration source (based on a deuterium-tritium generator to make ^{16}N) for Super-K. This calibration is critically important to the solar neutrino analysis effort. Our involvement on Super-K is supported through a separate NSF grant (with Sullivan as the PI) which provides support for that activity. This proposal, while primarily for Milagro, supports the summer salary for Dr. Sullivan for both Milagro and Super-K.

7.2 Milagro

Both Professors Sullivan and Goodman work on Milagro. In addition, we have three post-docs working full time on Milagro. Andy Smith has been a major player in the Milagro project, working on all aspects of the experiment. His background is in High Energy Physics and has been working on Milagro for three years (at UCR before Maryland). Javier Bussons Gordo recently joined Milagro coming from the Whipple experiment. Xie Wei is just joining Maryland and Milagro after doing his thesis research on air showers in Tibet and having been a post-doc on the Phenix heavy ion collider experiment.

8 Training and Education at Maryland

Particle Astrophysics is an exciting area to students and the general public. The Maryland group has been very active in conveying this excitement in a number of ways. Both Milagro and Super-Kamiokande experiments provide excellent training for students at all levels. We have had both graduate and undergraduate students working on both experiments.

8.1 Graduate Students

The Milagro project and Super-K, provide excellent educational opportunities for both undergraduate and graduate students. The size of the collaboration is modest and students are given the opportunity to participate in all aspects of the experiment. They gain experience in hardware, software and analysis. Zoa Conner was a Maryland graduate student and the first student (Japanese or American) to receive a Ph. D. on Super-K. She was involved in many aspects of the experiment including detector construction, calibration and analysis development. She received a highly prized Fermi Fellowship at the University of Chicago upon graduation from Maryland. Milagro will provide similar opportunities. Currently, Diane Evans is a Maryland graduate student working on Milagro.

8.2 Undergraduate Students

During the past five summers approximately more than 30 undergraduates have spent the summer at Los Alamos working on Milagro construction including five from Maryland. Maryland also has brought four undergraduates to Japan to work on Super-K. Many of these students have considered this the high point of their undergraduate careers. Of these students, all but one of the graduates has gone to graduate school in Physics.

8.3 Outreach

The Maryland group is active in educational outreach. Jordan Goodman has given many presentations on Milagro and other physics topics at area high schools and has worked with the US Physics Olympics team each spring for the past 14 years. He was awarded the University of Maryland Presidents award for service to the schools. In addition he was co-PI on an NSF educational grant to improve the engineering laboratories at Maryland. This project has been widely recognized in the community as having made a significant improvement to the engineering physics laboratories.

9 Budget

(*Note: Currently, the NSF is supporting two post-docs and summer salary for the two faculty members at Maryland. When Professor Goodman became Chair of the Physics Department, he negotiated that the College would provide his summer support and enough additional support to provide for a third Milagro post-doc. This proposal therefore requests support for two and one half post-docs, but no summer support for Goodman. As a result we get three post-docs for the same cost as two before.)*