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Milagro - A Low Energy Threshold Extensive Air Shower Array

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Observations of high-energy gamma rays from astronomical sources have revolutionized our view of the cosmos. Gamma rays with energies up to ~ 10 GeV can be observed directly with space-based instruments. Above 100 GeV the low flux of gamma rays requires one to utilize ground-based instruments. Milagro is a new type of gamma-ray detector based on water Čerenkov technology. This new design will enable Milagro to continuously observe the entire overhead sky, and be sensitive to cosmic rays with energies above ~ 250 GeV. These attributes make Milagro an ideal detector for the study of high-energy transient phenomenon.

1. INTRODUCTION

The EGRET instrument onboard the Compton Gamma Ray Observatory (CGRO) has shown that the high energy gamma-ray sky is highly variable. Their observations of gamma-ray bursts (GRBs) and active galaxies (AGN) beg for extending these observations to higher energies.

Milagro will be capable of continuously monitoring the entire overhead sky at energies between ~ 250 GeV and 50 TeV. This capability makes it the first detector to operate in this energy band that is sensitive to the transient phenomena that seem to be so ubiquitous in the universe. Thus current measurements made by air Čerenkov telescopes can be extended to higher energies, providing insight into pulsar acceleration mechanisms, high-energy particle production in active galaxies, and the extragalactic background light.

2. GROUND-BASED DETECTION OF COSMIC RAYS

When a high energy cosmic ray enters the earth's atmosphere it generates a shower of particles. The bulk of the primary's energy is transferred to electromagnetic particles, whether the primary cosmic ray was a photon or a nucleus. If the primary particle is a nucleus, hadronic interactions with air nuclei lead to the production of muons. Ground-based gamma-ray detectors can be divided into three classes: atmospheric Čerenkov telescopes (ACTs), extensive air

shower (EAS) arrays, and air fluorescence detectors (which we will not discuss).

As the shower develops and traverses the atmosphere the charged particles generate Čerenkov radiation in the atmosphere. This Čerenkov light continues propagating long after the bulk of the shower particles have died out. By employing large mirrors and fast electronics an ACT can detect this Čerenkov light above the night sky background. Since this is an optical technique, these detectors have a small field of view ($\sim 4 \times 10^{-3}$ sr) and can only operate on clear moonless nights. There is now a proven technique for removing much of the charged particle background - the imaging technique [1]. This development makes air Čerenkov telescopes very sensitive instruments. Though not well suited for sky surveys or looking for transient phenomena they can make very sensitive observations of known sources.

If the primary cosmic ray is sufficiently energetic, enough electromagnetic particles reach the ground to be detected with a sparse array of scintillation detectors. The shower particles travel in a pancake, roughly 50 m wide by 1 m thick. The pancake is perpendicular to the trajectory of the primary cosmic ray. The arrival direction of the primary particle can be determined by measuring the relative arrival times of the shower particles over a large area.

Extensive air shower arrays have large apertures and high duty factors. They can operate

night and day, rain or shine. Their field of view is essentially the entire overhead sky, though the effective energy threshold of these arrays increases rapidly with zenith angle ($\sim \cos^{-5.5} \theta$ [2]). The charged cosmic ray background can be reduced with the use of muon detectors, though this is not as effective (for known sources) as the imaging method employed by ACTs. Conventional EAS arrays have a high energy threshold, some 20-100 times that of air Čerenkov detectors.

One method of lowering the energy threshold of extensive air shower arrays is to increase the sampling of the air shower (typical EAS arrays sample between 0.5 and 1% of the electrons in an air shower). Water Čerenkov technology allows one to sample roughly 50% of the electromagnetic shower particles in a cost effective manner. Since energetic photons outnumber electrons by a ratio of $\sim 4:1$, water detectors have a distinct advantage over conventional thin scintillation detectors, which are not sensitive to photons.

3. THE MILAGRO DETECTOR

Milagro is a water-Čerenkov detector that will be located 35 miles northwest of Los Alamos in the mountains of northern New Mexico. The site is at an altitude of 8692' above sea level.

The heart of the Milagro detector is a 5 million gallon light-tight pond of water, on loan from a geothermal energy project. The pond has a surface area of 5,000 m², a bottom area of 1,500 m², and is 8 m deep (see Figure 1). There will be 3 layers of photomultiplier tubes (PMTs) in the pond. The top layer will have 450 PMTs arranged on a 3x3 m grid between 1 and 2 meters below the surface. The bottom layer of 170 PMTs will be 1 m above the bottom of the pond looking down. They will be optically isolated from the top of the pond and from each other. Each PMT in the bottom layer will sit in a 3x3x1 m box made of a reflective material. The middle layer of tubes will sit just above the bottom layer and face up. The pond will be surrounded by a sparse array of scintillators covering $\sim 30,000$ m².

The top layer of PMTs will be the 'air shower' layer. This layer will be used to trigger the entire detector and to reconstruct the direction and en-

Figure 1. Schematic view of a portion of the Milagro detector.

ergy of the primary cosmic ray. The middle layer will be a calorimetric layer, used to measure the energy deposited in the pond. It will also serve to measure any hadronic component of the air shower that reaches the pond. The bottom layer will serve as a large area muon detector, with an energy threshold for muons of $1.4/\cos(\theta)$ GeV.

When relativistic electrons and positrons enter the water, Čerenkov light will spread out in a 41° cone about the particles' trajectories. Photons in the air shower will convert to electrons and positrons in the top ~ 0.3 m of water. Figure 2 shows the expected effective area of the pond as a function of primary cosmic ray energy (for cosmic gamma rays and protons) for a 25 PMT multiplicity trigger. The low energy threshold, large area, and large aperture lead to an event rate of about 1 kHz.

The angular resolution of the detector depends on a number of factors: the number of particles that reach the ground, the timing distribution of these particles, the ability to locate the core of the air shower (the point where the primary particle would have hit the ground had there been no atmosphere), the geometry of the Čerenkov light, and the time jitter in the PMTs and electronics. Monte Carlo simulations of extensive air showers

Figure 2. Milagro effective area as a function of energy, solid line: gamma rays, dashed line: protons.

and the detector indicate that the angular resolution of the detector will be roughly 0.6° when 25 or more PMTs are struck and fall to 0.4° if 50 or more PMTs are struck.

4. PHYSICS WITH MILAGRO

Milagro will address a broad range of physics issues, from solar physics and pulsar models to cosmology and elementary particle physics. We will discuss three of these topics here - active galactic nuclei, gamma-ray bursts, and primordial black holes.

4.1. Active Galactic Nuclei

EGRET has detected over 40 AGN. All of these AGN have been classified as blazars. It is believed that the jets in blazars are pointing directly at the observer. Above 500 GeV, observations have been carried out using atmospheric Čerenkov telescopes. To date only 9 of the 40 AGNs have been viewed and they have only been observed for relatively short periods. Of these only 1 has been detected (Mrk 421). Mrk 421 is the closest and the weakest AGN observed by EGRET. The non-detection of the other AGN could be due to:

the transient nature of AGN, absorption at the AGN, or absorption of the gamma rays enroute to the earth by the extragalactic background light (EBL). (Absorption of high-energy gamma rays is due to the interaction $\gamma\gamma \rightarrow e^+e^-$ between the gamma ray and the ambient radiation field.) The latter possibility is perhaps the most exciting.

Observations of AGNs above 100 GeV could measure the extragalactic background light (EBL) [3-5]. The intensity of the EBL is determined by the epoch of galaxy formation, thus determination of the EBL may distinguish between cold dark matter (CDM) and cold+hot dark matter (CHDM) models of the Universe [5]. For a universe composed of CHDM Milagro can detect AGNs with a luminosity 5 times that of Mrk 421 at a redshift of ~ 0.4 .

4.2. Gamma-Ray Bursts

To date BATSE has detected over 1000 GRBs and the origin of this phenomena is still unknown. EGRET has shown that the spectrum of GRBs can extend beyond 10 GeV, with no sign of a cut-off. One especially energetic burst was observed to last for at least 2 hours by EGRET though the BATSE detector only detected emission of a few minutes [6].

If the spectrum of GRBs extends above 500 GeV, Milagro will detect them. For short bursts the cosmic-ray background ceases to be a problem and the full power of the detector is realized. As can be seen from Figure 2 Milagro has an effective area of $\sim 15 \text{ m}^2$ at 50 GeV, much greater than any space-based detector. In Table 1 we compare the sensitivity (minimum fluence necessary for a detection) of Milagro to that of BATSE, COMPTEL, and EGRET for 1 second bursts.

The detection of high-energy emission from GRBs would place severe constraints on the nature of the source. The emitting region must have a large bulk Lorentz factor to overcome the absorption of high-energy gamma rays in the intense photon field near these sources. Because of the absorption of high-energy gamma rays by the EBL, a detection of a GRB above $\sim 100 \text{ GeV}$ would indicate that they are closer than a redshift of 0.5.

Table 1

Sensitivities of BATSE, COMPTEL, EGRET, and Milagro (in ergs cm⁻²) to a 1 second burst of gamma radiation.

	BATSE[7]	COMPTEL[8]	EGRET[9]	Milagro
Energy (GeV)	2×10^{-5}	1×10^{-3}	0.03	500.
Sensitivity (ergs cm ⁻²)	1.0×10^{-7}	8.4×10^{-7}	7×10^{-7}	2×10^{-7}

4.3. Primordial Black Holes

Density fluctuations in the early universe could have led to the formation of $\sim 10^{15}$ g black holes, known as primordial black holes (PBHs). Stephen Hawking showed that black holes have a temperature $T = 10^{13}/M$ GeV [10]. As with all gravitationally bound systems, the specific heat of a black hole is negative. Therefore a PBH will evaporate as it attempts to attain equilibrium with the 3 K radiation field. The hole evaporates via emission of all particles with a rest mass less than $\sim 5T$. The luminosity of a black hole is given by $\mathcal{L} = f/T^2$ where f depends on the number of available particle states. A measurement of the time evolution of the luminosity of a black hole can thus determine the elementary particle spectrum at arbitrarily high energies.

Currently the best limits on the density of PBHs comes from the diffuse gamma-ray flux at 100 MeV. This limit can not be directly compared to limits derived from direct searches for the final explosion of the PBH. The latter limits are sensitive to PBHs in the solar neighborhood, while the limit derived from the 100 MeV gamma rays depends only on the total amount of matter bound in PBHs. Thus to compare the two limits one must make assumptions about the clustering of PBHs. If PBHs do not cluster, then the 100 MeV limit implies that there are fewer than 10^{-6} explosions pc⁻³ yr⁻¹ [11]. If PBHs are clustered like galactic matter the rate-density would be 10^7 times greater, and if they cluster within solar systems the rate-density could be as high as 10^7 explosions pc⁻³ yr⁻¹.

Currently the best direct limit has been set by the CYGNUS EAS array - $< 8.5 \times 10^5$ explosions pc⁻³ yr⁻¹ [12]. Because of its low energy threshold (and the steep energy spectrum of PBHs) Milagro can improve on this direct limit by over 2 orders of magnitude.

5. CONCLUSIONS

The TeV gamma-ray universe is just beginning to come into view. To date narrow aperture, short duty cycle telescopes have examined a small fraction of the sky and detected a handful of sources. Milagro will be the first instrument capable of continuously monitoring the entire overhead sky above 250 GeV. As such it is an ideal instrument for studying the highly variable and transient high-energy universe.

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