SURVEYING THE TEV SKY WITH MILAGRO

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Abstract

A wide field of view, high duty factor TeV gamma-ray observatory is essential for studying TeV astrophysical sources, because most of these sources are either highly variable or are extended. Milagro is such a TeV detector and has performed the deepest survey of the Northern Hemisphere sky at TeV energies. In addition to detecting the Crab Nebula and Mrk 421, which are known TeV sources, Milagro has made the first detection of diffuse TeV emission from the Galactic plane. The Milagro data has been searched for unknown point sources and extended sources. Recently the Milagro Collaboration has reported the detection of very high energy (VHE) gamma rays from the Cygnus Region. In this region evidence for diffuse emission and for a new TeV source, coincident with an EGRET unidentified source, is seen. Milagro has also performed a search for very high energy gamma rays from GRBs. The Milagro data has also been searched for TeV emission from gamma-ray bursts, galaxy clusters, and EGRET unidentified sources. Solar energetic particles from coronal mass ejections have been detected by Milagro.

1 The Milagro detector

Milagro is a water Cherenkov extensive air-shower detector located near Los Alamos, in New Mexico at 2630 m above sea level, consisting of a $5,000\,\mathrm{m}^2$ central (pond) detector surrounded by an array of 175 equipped water tanks, (outriggers) that extends over an area of roughly $40,000\,\mathrm{m}^2$. The central detector is equipped with 723 photomultiplier tubes arranged into two layers, the air-shower layer and the muon layer. Unlike scintillation arrays, the Milagro pond densely samples the extensive air-shower particles that reach the ground. Since the Cherenkov angle in water is 41 degrees, an array of photomultiplier tubes (PMTs) placed at a depth roughly equal to their spacing can detect nearly all of the particles that enter the water. The large aperture and exposure of Milagro make it ideal to survey the very high energy gamma ray sky and continuously perform searches for transient sources. (Smith, 2005)

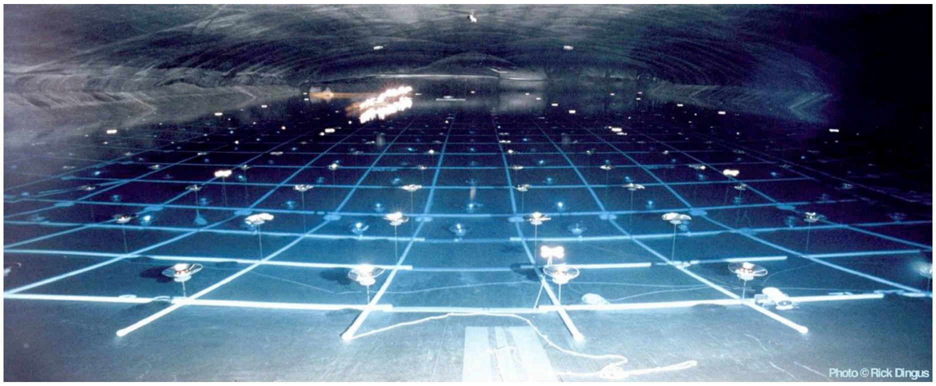

Figure 1: The Milagro pond with the cover inflated for servicing. Both the top and the bottom layers attached to the grid can be seen.

The directions of gamma rays hitting the atmosphere are reconstructed through the detection of air-shower particles that reach the ground level. The shower particles are detected in the central pond. The air-shower layer is situated at a depth of 1.4 m below the surface of the pond. The shallow depth allows the accurate measurement of shower particle arrival times used for direction reconstruction and triggering. The muon layer is located 5 m below the water surface. The greater depth is used to detect the presence of penetrating muons and hadrons. Monte Carlo simulations suggest that γ-initiated air-showers illuminate the muon layer uniformly, whereas hadronic-initiated air-showers form bright, compact clusters of light. Several parameters been developed by the Milagro Collaboration to distinguish between gamma-ray induced and hadron induced air-showers using the pattern of hits in the bottom layer (Atkins et al, 2003, Abdo, 2006).

The median energy of the gamma rays Milagro detects varies with energy spectrum, declination of the source, and background criteria. The median energy for the Milagro experiment is 3.5 TeV for the data analysis performed using the compactness parameter X_2 for the background rejection (Atkins et al, 2003). For the analysis of the gamma ray emission from the Galaxy the parameter A_4 for the background rejection was adopted and the median energy for this analysis increased to 12.5 TeV (Abdo, 2006). The Milagro angular resolution was 0.75 degrees, which was recently improved to 0.3 degrees when the outriggers were added to the reconstruction and the new parameter A_4 was adopted.

Figure 2: Aerial view of the Milagro detector. The central pond is visible and the red dots indicate the locations of the outriggers.

Here we present the observations of gamma ray emission from the Galaxy and the searches of very high energy gamma rays from GRBs done by the Milagro detector in 5 years of operations, from 2001 to 2006.

2 Detection of TeV gamma ray emission from the Galaxy

The diffuse Galactic γ-ray emission is believed to be mostly produced in interactions of cosmic rays with the matter and the radiation fields in the Galaxy, the main production mechanisms being electron non-thermal

Bremsstrahlung, Inverse Compton scatterings off the radiation fields and pion decay processes in inelastic collisions of nuclei and matter. Although the standard production mechanisms of γ-rays (Bertsch, 1993) accurately predicts the spatial and energy distribution of the emission below 1 GeV, the model does not match EGRET observations of the γ-ray sky above 1 GeV. (Hunter, 1997) The discrepancy between the model and the observations is more pronounced towards the direction of the inner Galaxy, where it amounts to 60 per cent of the observed emission. In the standard model gamma rays above 1 GeV are mainly produced in hadronic interactions and their spectrum should follow the cosmic ray spectrum. Instead the spectral index of the emission observed by EGRET at energies above 1 GeV is roughly -2.4, significantly harder than the cosmic ray spectrum. In order to understand how GeV γ-rays are produced it is fundamental to observe the γ-ray flux at higher energies and determine its spectrum.

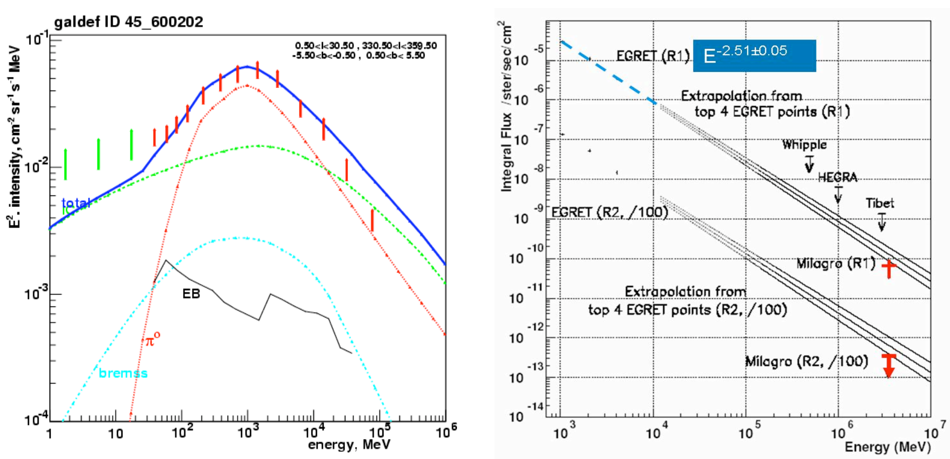

Figure 3: On the left side the predictions of the optimized model by Strong et al, 2004 for the galactic diffuse emission, compared to EGRET data points from the inner Galaxy. On the right side the gamma ray integral flux measured by Milagro and EGRET from the region R_1 and the upper limit from the region R_2 in the Galaxy. Also shown are the 99 per cent c.l. upper limits from Whipple (LeBohec et al, 2000), HEGRA (Aharonian et al, 2001) and Tibet (Amenomori et al, 2002)

Using the data collected in the first three years of operation Milagro reported the detection of TeV gamma ray from a region in the Galaxy called R_1, with longitude $40^0 < l < 100^0$ and latitude $|b| < 5^0$, the inner Galaxy for Milagro (Atkins et al, 2005). The observed excess from the inner Galaxy has a significance of 4.5 standard deviations. The best fit value for the flux above 3.5 TeV is $\Phi_\gamma = (7.3 \pm 1.5 \pm 2.2) \times 10^{-11}\, cm^{-2}\, s^{-1}\, sr^{-1}$ and for the differential spectral index are $\alpha_\gamma = 2.61 \pm 0.03 \pm 0.06$. A fit to the four highest EGRET energy measurements (between 1 GeV and 30 GeV) in R_1 yields a differential spectral index of $\alpha_{EGRET} = 2.51 \pm 0.05$, consistent with the result from Milagro. For the outer Galaxy, the region R_2 with longitude $100^0 < l < 200^0$ and latitude $|b| < 5^0$, Milagro reported a 99 per cent confidence level upper limit to the flux of $\Phi_\gamma = 5.0 \times 10^{-11}\, cm^{-2}\, s^{-1}\, sr^{-1}$. In Fig. 3 the Milagro measurements in R_1 and the upper limit in R_2 along with the extrapolation from the highest four EGRET data points is shown. The Milagro result seems to exclude an additional hard spectrum component continuing to above 10 TeV to explain the 60 per cent excess of EGRET flux compared to π_0-decay production mechanism due to the local cosmic ray flux. No significant excess was detected from the region R_2. The upper limits put on the emission from the region R_2 seem to indicate a softening of the spectrum in the outer Galaxy.

3 Detection of TeV gamma ray emission from the Cygnus region

Milagro has surveyed the northern sky in search of point-like and extended sources for five years. Recently the Milagro Collaboration reported the detection of TeV energy gamma rays from the Cygnus Region (Smith, 2005). The Cygnus Region in the Galaxy is the brightest region of the northern sky reported by EGRET in the energy range between 30 MeV and 30 GeV. The regions hosts many Wolf-Rayet stars, OB associations, and supernova remnants, good candidates to be sites of particle acceleration. (Plüschke et al, 2001) The Cygnus Region is also extremely rich in molecular Hydrogen, a signal of intense star formation activity (Dame et al, 2001).

The discovery of high energy emission from the Cygnus Region has significant consequences on our understanding of cosmic ray acceleration and propagation in the Galaxy. In the Cygnus Region Milagro observed patterns of both diffuse γ emission, originated by accelerated particles diffusing in the Galaxy and interacting with the local matter and radiation fields, and more localized emission, possibly originated from in situ acceleration of cosmic rays. In particular, Milagro detected VHE gammas at about 12 σ from a source at right ascension $RA = 305^0$ and declination $\delta = 37^0$, which seems to coincide with two EGRET unidentified sources. The median en-

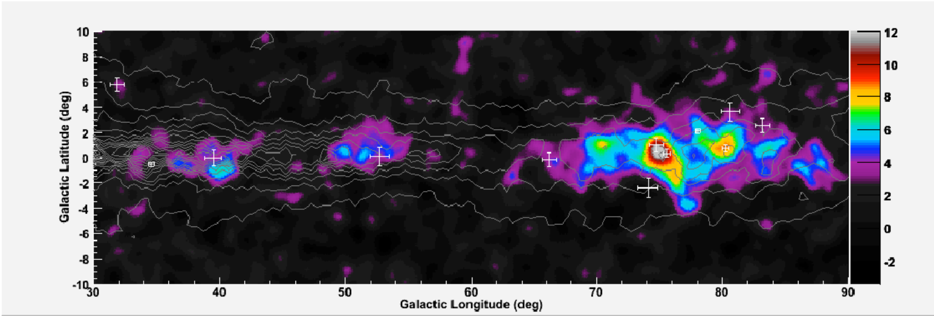

Figure 4: The inner Galaxy surveyed by Milagro in galactic coordinates. The Galactic Ridge, the Cygnus Region (with longitude $65 < l < 90$) and a strong source within the Cygnus Region at 6.5 σ above the average are clearly visible. The features of gamma ray diffuse emission and of localized emission from sources can both be seen. The crosses in the figure show the location and location error of the EGRET sources in this region (none of which have been definitively identified with counterparts at other wavelengths).

ergy for these observations is 12.5 TeV. While the average angular resolution of Milagro for a single gamma ray is 0.5 degrees, the highest energy gamma rays detected have substantially better angular resolution (0.3 degrees) and background rejection. An examination of the arrival directions of the higher-energy photons shows that this source is most likely an extended source of TeV gamma rays. In Fig. 4 the Milagro detection of high energy gamma rays from the inner Galaxy is shown. A more detailed analysis of the Milagro data will be published soon.

4 Gamma Ray Bursts in Milagro

According to some authors (Gonzalez et al, 2003, Hurley et al, 1994, Atkins, et al, 2002) TeV photons are created during the prompt phase, either through proton synchrotron or inverse Compton. For such distant sources as GRBs, TeV photons are mostly absorbed through pair production with cosmic background radiation (CBR) (Stecker & Jager 1998, Primack et al, 1999, Primack et al, 2005 model. Kneiske et al, 2004), but some indications of TeV gamma rays from GRBs at low redshift were provided by experiments like Milagro (Atkins et al, 2000), Hegra (Padilla et al, 1998) and Tibet (Amenomori et al, 1996).

Milagro's large field of view (2 steradians) and high duty cycle (more than

90 per cent), allow it to observe a large portion of the sky, nearly all the time, making it well suited to searching for the transient emission produced by GRBs or other sources of short duration VHE gamma-ray flares. The median energy of the events detected by Milagro is a few TeV, however the effective area is still large at hundreds of GeV (about $50\,\mathrm{m}^2$ at 100 GeV). This results in a gamma-ray fluence sensitivity at VHE energies comparable to previous satellite detectors at keV energies (Noyes, 2005)

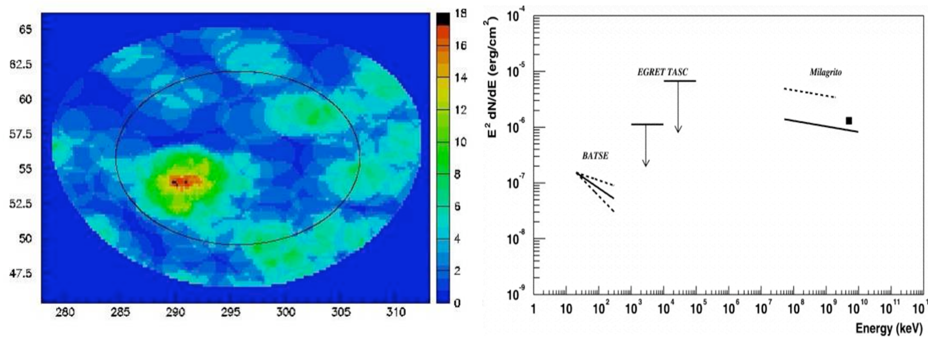

Figure 5: On the left side the number of events recorded by Milagrito during T90 in overlapping 1.6 degree radius in the vicinity of GRB 970417. On the right side the spectral energy distribution showing a single power-law fit to the BATSE data, upper limits at 1 MeV and 10 MeV from EGRET, and three possible spectral forms consistent with the Milagrito observations.

Milagrito, the prototype of Milagro, searched for VHE emission in the 54 BATSE bursts which happened in its field of view and reported evidence for emission above 650 GeV from GRB 970417a with a post-trials probability of 1.5×10^{-3} of being a background fluctuation. (Atkins et al, 2000, Atkins et al, 2003) During the year Milagrito operated, 54 GRBs within its field of view occurred at relatively low redshift. Between 2002 and 2004 only 4 GRBs per year occurred in Milagro fov with $z < 0.3$. The number of GRBs per year has increased since Swift was launched. However, the redshift of Swift GRBs is significantly higher than that of the BATSE sample, the average Swift redshift being about 2.5. Since Milagro started its operation about 72 GRBs have occurred within its field of view. No significant emission was detected from any of these bursts. In Table 1 the upper limits on the GRBs which occurred in Milagro field of view between 2002 and 2005 are shown. (Saz Parkinson, 2005)

Milagro has also performed a search for GRBs not triggered by satel-

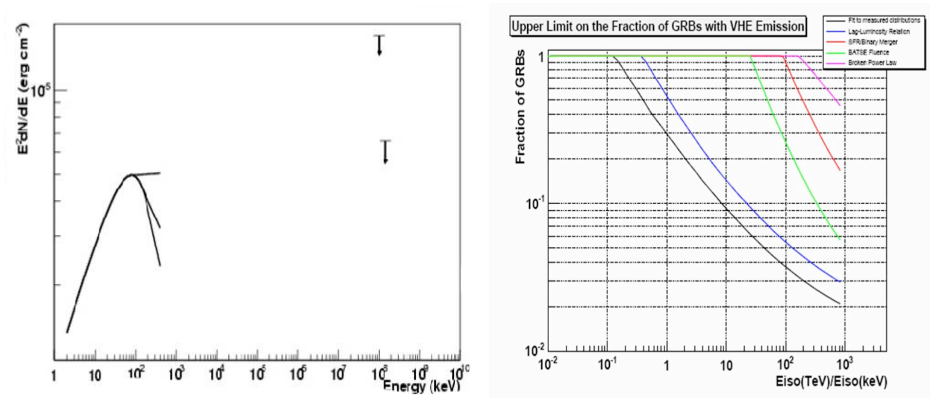

Figure 6: On the left side Milagro upper limits on GRB 010921. The spectrum in the range between 2 and 400 keV was measured by HETE. The high energy spectral index was not constrained, so the spectra for -1.99, -2.33 and -2.67 are plotted. The arrows indicate the upper limits from Milagro for various absorption models, the higher one from Stecker & Jager, 1998, and Primack et al, 1999. The lower arrow is from the more recent Primack et al, 2005 model. On the right the upper limits on the fraction of GRBs with a VHE component plotted vs. the ratio of keV-MeV and VHE fluence for several redshift models. (Noyes, 2005).

lite detection. It is possible to search the Milagro data for VHE emission from GRBs by searching over the entire sky, at all times, and over multiple durations. The search is done in real time over 27 durations ranging from 250 μs to 2 hours. In this time period we know that 200 GRBs must have occurred in Milagro field of view. Based on the fact that no evidence for VHE emission from a GRB was observed it is possible to constrain the VHE component of the GRB spectrum. In Fig. 6 the upper limits on the fraction of GRBs with a VHE component plotted versus the ratio of keV-MeV and VHE fluence for several redshift models are shown.

5 Conclusions

Milagro is a unique VHE gamma-ray observatory capable of continuously monitoring the overhead sky. Its field of view of 2 steradians, its good background rejection, its high duty cycle and the large area make it complementary to other high energy gamma ray detectors such as the air Cherenkov telescopes or satellite missions. In addition to detecting the Crab Nebula and Mrk 421, which are known TeV sources, Milagro has made the first detection of diffuse TeV emission from the Galactic plane. The Milagro

GRB	Instrument	UTC	RA,Dec. (deg.)	T90/Dur. (s)	θ (deg.)	z	Li-Ma σ	99% UL fluence (erg cm^2)
020625b	HETE	41149.3	310.9,+7.1	125	38.1	...	1.4	5.7e-6
021104	HETE	25262.9	58.5,+38.0	19.7	13.3	...	0.9	7.5e-7
021112	HETE	12495.9	39.3,+48.9	7.1	33.6	...	-0.1	9.4e-7
021113	HETE	23936.9	23.5,+40.5	20	17.7	...	0.1	6.4e-7
021211	HETE	40714.0	122.3,+6.7	6	34.8	1.01	2.0	1.7e-06*
030413	IPN	27277.0	198.6,+62.4	15	27.1	...	0.8	1.0e-6
030823	HETE	31960.6	322.7,+22.0	56	33.4	...	1.0	2.8e-6
031026	HETE	20143.3	49.7,+28.4	114.2	33.0	...	0.7	3.8e-6
031220	HETE	12596.7	69.9,+7.4	23.7	43.4	...	0.2	4.0e-6
040924	HETE	42731.4	31.6,+16.0	0.6	43.3	0.859	-0.6	1.5e-06*
041211	HETE	41507.0	101.0,+20.3	30.2	42.8	...	0.9	4.8e-6
041219	INTEGRAL	6400.0	6.1,+62.8	520	26.9	...	1.7	5.8e-6
050124	Swift	41403.0	192.9,+13.0	4	23.0	...	-0.8	3.0e-7
050319	Swift	34278.4	154.2,+43.5	15	45.1	3.24	0.6	4.4e-06*
050402	Swift	22194.6	136.5,+16.6	8	40.4	...	0.6	2.1e-6
050412	Swift	20642.9	181.1,-1.3	26	37.1	...	-0.6	1.7e-6
050502	INTEGRAL	8057.7	202.4,+42.7	20	42.7	3.793	0.6	3.8e-06*
050504	INTEGRAL	28859.1	201.0,+40.7	80	27.6	...	-0.8	1.3e-6
050505	Swift	84141.1	141.8,+30.3	60	28.9	4.3	1.2	2.3e-06*
050509b	Swift	14419.2	189.1,+29.0	0.03	10.0	0.225	-0.9	9.2e-08*
050522	INTEGRAL	21621.0	200.1,+24.8	15	22.8	...	-0.6	5.1e-7
050607	Swift	33082.7	300.2,+9.1	26.5	29.3	...	-0.9	8.9e-7

Table 1: GRBs in the field of view of Milagro in 2002–2005. The upper limits assume the burst was nearby (z=0). Those with a (*) next to them have a measured redshift, making this assumption invalid. The upper limits assume also that in the range between 0.25 to 25 TeV the GRB spectra are power law spectra with spectral index -2.4. GRB 050509b is the first short/hard burst for which an afterglow emission was detected. GRB 050509b is relatively nearby (redshift 0.225) and occurred at a zenith angle of 10 degrees for Milagro. An upper limit of $5.4 \times 10^{-8}\, erg\, cm^{-2}$ at 2.5 TeV is provided. (Saz Parkinson, 2005)

data has been searched for unknown point sources and extended sources. Recently the Milagro Collaboration has reported the detection of very high energy (VHE) gamma rays from the Cygnus Region. In this region evidence for diffuse emission and for a new TeV source, coincident with an EGRET unidentified source, is seen. The Milagro data has also been searched for TeV emission from gamma-ray bursts, galaxy clusters, and EGRET unidentified sources. Solar energetic particles from coronal mass ejections have been detected by Milagro. Based on the success of Milagro, a second generation water Cherenkov gamma-ray observatory is planned which will give an increase in sensitivity of more than an order of magnitude.

6 Acknowledgments

We acknowledge Scott Delay and Michael Schneider for their dedicated efforts in the construction and maintenance of the Milagro experiment. This work has been supported by the National Science Foundation the US Department of Energy, Los Alamos National Laboratory, the University of California, and the Institute of Geophysics and Planetary Physics.

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DISCUSSION

TODOR STANEV: Does Milagro use the water tanks for shower reconstruction ?

On average the PMTs in the pond will detect most of all electromagnetic particles that enter the pond. This sensitivity allows for the detection of extensive air showers with cores far from the pond (over 100 meters away). The shower front is not a plane, but is curved. Therefore, if the core of the air shower is outside the pond a fitted shower plane, using the wrong core position, will not be perpendicular to the true direction of the primary particle. This effect tends to degrade the angular resolution of Milagro. By adding the outriggers we can determine the core position when the core falls outside the pond. This not only improves the angular resolution, it also allows us to make an estimate of the shower energy for these events and improves our gamma hadron separation. Specifically, our simulations predict an energy resolution of about 75 per cent at 1 TeV improving to about 50 per cent at 10 TeV. (Our energy resolution is approximately lognormal, so if we measure 10 TeV, 5 TeV is 1 sigma and 2.5 TeV is 2 sigma). The combined effect of the outriggers is conservatively expected from simulations to improve significance on a Crab-like source by approximately a factor of two. This means that we get the same signal at least four times quicker.

ARNON DAR's comment: Since Swift GRBs have mostly a high redshift, Milagro should look for X-ray flashes, whose average redshift is lower.

The Milagro data are searched for GRBs or other sources of short duration VHE gamma-ray flares over the entire sky, at all times, and over multiple durations. The search is done in real time over 27 durations ranging from 250 μs to 2 hours.

ANDREA SANTANGELO: What is the role of Milagro/miniHAWC in view of the new ACT project ?

Milagro's high duty cycle and large field of view makes it a unique tool to perform a continuous survey of TeV sky in search of extended and transient sources. The Milagro Collaboration will submit to the National Science Foundation (NSF) and to the Department of Energy (DOE) the project for a future water Cherenkov detector called miniHAWC. The simple design improvements (higher altitude and larger physical area) of miniHAWC, will significantly improve the detector sensitivity and decrease its energy threshold. The wide field of view, good hadron rejection, high duty cycle, and large area of Milagro and of the next generation of water Cherenkov detectors (miniHAWC) make them complementary to other forefront high energy gamma ray detectors.