Gamma Ray Astronomy with Air Shower Arrays
TeV Gamma-Ray Astrophysics

- Study sources of TeV Gamma Rays
  - Neutron stars and pulsars
    Crab is the “Standard candle”
    Other sources including Vela and PSR 1706−44
  - AGN
    Variability on time scale of hours and longer observed.
    Some of the sources include Mrk 421 (Z=0.031), Mrk 501 (Z=0.033), 1ES 2344+514 (Z=0.044)
  - Galactic plane
  - Gamma Ray Bursts
  - Primordial Black Holes?
  - WIMPS collected by the sun?
  - ???

- Study medium between source and observer.
  Loss due to infrared background.

\[ \lambda = \frac{2.7 \text{ Mpc}}{\rho[\text{pts/cm}^3]f(\beta)} \]

where \( \beta = \sqrt{1 - m^2/k'^2} \), \( k' \) is the cm photon momentum,

\[ f(\beta) = (1 - \beta^2) \cdot [(3 - \beta^4) \ln \left( \frac{1 + \beta}{1 - \beta} \right) + 2\beta(\beta^2 - 2)] \]

\[ 0 \leq f(\beta) \leq 1.4, \text{ and } f(\beta) \text{ is maximum at } \beta \sim 0.7 \]

For a 1 TeV \( \gamma \) threshold for a head-on collision is with a \( \sim 0.5 \text{ eV } \gamma \).

- Background is \( \sim \) isotropic cosmic rays, but can study:
  - Moon shadow \( \rightarrow \) detector resolution, earth’s B field effects.
  - Shadowing by the sun \( \rightarrow \) solar B\( _\perp \)
  - Solar energetic particles.
  - Cosmic ray composition.
“First Generation” Pointing Air Shower Experiments:

- Cygnus Experiment
  - April 1986 to \( \sim \) 1997.
  - Energy \( \geq 10 \) TeV, median energy \( \sim 40 \) TeV
  - Angular resolution \( \sim 0^\circ.75 \)
  - First observation of sun and moon shadowing.

- CASA
  - Energy \( \geq 100 \) TeV
  - Angular resolution \( \sim 0^\circ.8 \) for cores on array.
  - Observation of sun and moon shadowing.

- Tibet Air Shower Array
  - Began operation January 1990.
  - Energy \( \geq 3 \) TeV, peak \( \sim 7 \) TeV.
  - Angular resolution \( \sim 0^\circ.6 \) if 2D Gaussian assumed.
  - Observation of sun and moon shadowing.

- Unconfirmed episodic observations reported in 1980s by various experiments.
Goals and Requirements

Study VHE photons from ground based observatory by measuring the atmospheric particle shower that the primary photons produce.

- Large angular acceptance and 24-7 Operation.
  - Study particles surviving to detector altitude, thus allowing daytime operation, and even viewing of the sun!
  - Use particle arrival time lateral distribution to determine primary incidence angle. Angular acceptance determined by atmospheric depth which increases as \(1/cos\theta\) from the vertical.
  - Use signal size distribution to measure primary energy.

- Lower energy threshold - conventional air shower arrays become sensitive at \(\sim 50\) TeV, since we are looking at “Calorimeter punch-through”.
  - Maximize altitude.
  - Maximize active area.
  - Sensitivity to shower photons, not just charged particles.

- Look for gamma signal over large, isotropic nuclear cosmic-ray background.
  - Angular resolution.
  - Gamma - Hadron separation.
  - Where possible, time/space search region defined by other observations.

- Healthy Mistrust of Monte Carlo.
  - Particle physics mostly understood (CORSIKA) but still some nuclear physics questions.
  - Main uncertainties at these energies are due to the details of detector properties.
The Milagro Collaboration

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The Milagro Site
The Milagro Method

This transparency will be a multi-layer one that shows how:

gamma ray hits the top of the atmosphere
EAS develops
particles hit the pond and PMTs
Shower plane is reconstructed
A Milagrito Event Showing PMT Times and Pulse Heights
A summary of the Milagrito prototype of Milagro

- Specifications
  - 228 PMTs, 8”-diameter, on a 2.8 m, 19x12 grid.
  - February 8, 1997 to May 7, 1998. Live time 79.5% with down time mainly due to power outages (~11.5%), calibrations (~3%) and maintenance and construction (~3%). Rest hardware or software errors.
  - A total of $8.9 \times 10^9$ events for PMTs at depths of 0.9 m (300Hz, $5.3 \times 10^9$ events), 1.5 m (340Hz, $1.1 \times 10^9$ events), and 2m (400Hz, $2.5 \times 10^9$ events).

- Behavior:
  - For crab-like ($E^{-2.5}$) spectrum, peak energy ~ 1 TeV if overhead ~ 1.5 TeV for the Crab.
  - Angular resolution depends on $N_{\text{FIT}}$, about 1 degree.
  - Effective area ~ geometric area at about 500 GeV for protons and $\gamma$.

- Some checks of technique and lessons learned:
  - Optimize water depth for angular resolution.
  - Baffles to get rid of late light.
  - Test of monte carlo
    Cosmic ray trigger rate: For $\delta_{\text{Mrk501}} = 39^\circ.8$, 1 degree radius bin, measure $2420 \pm 80$ events per day, calculate $2460^{+160}_{-90}$ from cosmic rays.
    Zenith angle distribution.
    Angular resolution as tested with $\Delta_{EO}$.
    Moon shadow versus point spread function.
Milagrito Data Monte-Carlo Comparisons:

$\Delta_{EO}$

$\theta$

ZENITH
**Milagrito Physics, Completed or On-going:**

- Moon Shadow, anti-proton search.
- Sun Shadow.
- SEP Event.
- Mrk 501.
- GRB 970417a.
- All-sky source search.
- Untriggered GRB search.
- Some additional source studies in progress.
- Some additional analyses which are possible will be not be performed because Milagro data is available.
Milagrito Moon and Sun Shadows

Significance of Excess in Vicinity of Moon

1°.7 square bins
Moon signal is 10.2 $\sigma$
Median energy 2.7 TeV
$\bar{p}/p$ 95% limit =17%

Significance of Excess in Vicinity of Sun

Milagrito Sun Shadow

Sun signal is 10.1 $\sigma$
Solar Energetic Particles from 6 Nov. 1997 Event

![Graph showing effective area and kinetic energy relationship](image)

**Effective Area to Isotropic p⁺'s deduced from Monte Carlo**

Milagrito High Thresh. Scaler

Milagrito 100 PMT trigger

IGY neutron monitor (at location of Climax)

![Graph showing Milagrito and Climax data](image)

Climax neutron monitor

Milagrito high threshold scaler

Milagrito 100 PMT trigger

Probability of background fluctuation < $2 \times 10^{-4}$
Milagrito Markarian 501 Results

Observed 918954 events in 1 degree radius bin.
Average expected 915330 ± 250
Excess is 3624 ± 990 = 3.7σ

Shaded region has Mrk 501 visible during the day, so no ACT data.
GRB 970417a

BATSE:

RA $= 295^\circ.7$, $\delta = 55^\circ.8$, uncertainty $\sim 6^\circ.2$, $T_{90} = 7.9$ sec.
Fluence (20 to 300 KeV) $1.5 \times 10^{-7}$ ergs/cm$^2$

Milagrito

Search $9^\circ.4$ radius area with $1^\circ.6$ radius bins, $0^\circ.2$ spacing.
18 events with avg background 3.46, probability $2.8 \times 10^{-5}$
RA $= 289^\circ.9$ $\delta = 54^\circ.0$ uncertainty $\sim \pm 0^\circ.5$
Probability of Background fluctuation is $10^{-3}$
Fluence calculation:

- Depends on assumed spectrum, $\frac{dN}{dE} = AE^{-\gamma}$ for $E < E_C$.
- $\int A_{eff}(E)\Phi(E)dE =$ observed number of events $\rightarrow A$.
- Scalar rate sets a limit on low energy particle flux.
- Can exclude $\gamma > 2.8$, $E_C < 700 GeV$. Typical fluence above 1 TeV $\sim$ order of magnitude $>$ at BATSE energy.
Milagrito All-Sky Source Search

δ:
2.2222° bins

RA:
2.2222°/cosδ bins

Typical upper limit compared with the Crab flux.
Milagro Design and Operation

- High altitude and large active area, photon sensitivity.
  - Altitude is 2650m (750 g/cm²).
  - PMTs provide full area coverage.
  - Photons pair produce or Compton scatter in 1.4m of water above the PMT, giving rise to energetic charged particles.

- History:
  - Engineering run started July 1999.
  - Physics run started December 1999.

- Behavior:
  - Excluding Los Alamos fire, > 95% duty cycle.
  - Data Rate \( \sim 1.5 \text{ kHz} \)

\[ \begin{array}{c|c|c|c|c}
\text{mjd} & 0 & 0.2 & 0.4 & 0.6 \\
\text{exposure (days)} & 0.8 & 1 & 1.2 & 1.4 \\
\hline
\text{mjd} & 1400 & 1500 & 1600 & 1700 & 1800 & 1900 \\
\text{average rate (Hz)} & 0 & 250 & 500 & 750 & 1000 & 1250 & 1500 & 1750 & 2000 \\
\end{array} \]

- Sensitive to about 200 GeV to 50 TeV.
- Resolution \( \sim 0.75 \) degrees.

- Monte-Carlo Data comparisons in progress.
• Gamma - Hadron separation

- Multi-layer measurements.
  
  450 Shower layer PMTs under 1.4 m of water.
  273 Muon layer under 6 m of water.

- Currently using:

  Clumpy hadron showers give few PMTs with large signals.

  \[ X_2 \equiv \frac{\text{Number bottom PMTs} > 2\text{PE pulse height}}{\text{Max bottom layer pulse height}} > 2.5 \]

Cut \( X_2 > 2.5 \)
retain 54\% of \( \gamma \)
reject 91\% of hadrons

\[ Q \equiv \frac{S_{\text{CUT}}/\sqrt{B_{\text{CUT}}}}{S/\sqrt{B}} \]
\[ Q = 1.8 \]
A Milagro Event Showing PMT Times and Fit Plane
Milagro Exposure, 60 Days of Data

Bins are $0.5^\circ$ in $\delta$ by $1.0^\circ$ in $\text{RA} \times \cos \delta$
Ongoing Milagro Studies

- Crab
- AGNs
- Moon Shadow
- Sun shadow
- Neutralinos
- Galaxy
- Surviving single hadrons
- Keep looking for GRBs...
Milagro Crab Signal

NF > 20, X2 > 2.5, 2.1 deg bin

Distribution of $\sigma$

<table>
<thead>
<tr>
<th>Number events</th>
<th>Expected BG</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>No $X_2$ Cut</td>
<td>6,739,156</td>
<td>6,735,122</td>
</tr>
<tr>
<td>$X_2 &gt; 2.5$</td>
<td>622,536</td>
<td>618,766</td>
</tr>
</tbody>
</table>
Milagro Crab Signal Accumulation

Milagro Crab Data: NF ≥ 20, X₂ ≥ 2.5

Milagro accumulates about 10 Crab photons per day.
Milagro Markarian 421

Mrk421: NFIT>20, X2>2.5, 2.1deg bin, Dec 20, 2000 - Feb 11, 2001

- Data recorded December 15, 2000 to March 1, 2001
- 154,391 on source events
- Expected BG 153,281
- Signal significance $\sim 2.95\sigma$
- Dots: BATSE GRB summed fluence vs. $T_{90}$.
- Curve: Milagro sensitivity for fluence above 1 TeV vs. $T_{90}$ for a triggered burst.

  Does not include $\gamma$/hadron separation (For current $X_2$ cut, this would lower threshold by $\sim 2$.)

  Does not include outriggers, which would lower threshold by $\sim 2$. 
The Milagro Future

- Improve Gamma - Hadron separation
  
  ACT breakthrough with 1989 Whipple \( \gamma / \text{hadron} \) cut.
  
  Milagro currently using:
  
  - \( X_2 \)
  
  Additional parameters:
  
  - \( \text{Nhit}_{\text{bottom}} \)
  
  - Shower signal rise time for muon elimination and \( \gamma / \text{hadron} \) separation.
  
  - Lateral signal distribution.

- Building Outriggers
  
  Contain EAS, area \( \sim 10 \) times Milagro.
  
  Improve angular resolution for core not on pond.
  
  Energy resolution \( \sim 50\% \) using Lateral distribution fit.
  
  Allows lowering energy threshold by vetoing isolated muons.
Milagro Outrigger Deployment
Outrigger Angular Resolution Improvement

Median Angle Error versus Core Distance

Space Angle Errors With and Without Outriggers

# of Events

Space Angle Error (deg)
Milagro Energy Resolution with Outriggers
The ARGO-YBJ Experiment Location
The ARGO-YBJ Experiment Layout

Main Building with RPCs

Detector carpet: $13 \times 13$ Clusters, 1560 RPC
Sampling ring: $6 \times 4$ Clusters, 288 RPC
Total: 154 Clusters, 1848 RPC
For a complete coverage another 84 Clusters ($1008$ RPC) are needed
The ARGO-YBJ Collaboration

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**ARGO-YBJ**

- Maximize altitude and active area, photon sensitivity.
  
  Altitude is 4300m (606 g/cm²).
  
  Resistive Plate Chambers (RPC) allow large coverage:
  - Each RPC is constructed of 10 pads each 0.60 m x 0.56 m
  - 92% of 78m x 74m
  - Additional 20% of remaining area inside 111m x 99m
  - Total of 6700 m² active area.

  0.5 cm Pb on RPCs converts γs.

- Expected Properties:
  
  Sensitivity 5σ in 1 year for ~1/10 Crab from 100 Gev to 20 TeV.
  
  Angular resolution ~ 0°.4 for 100 pad multiplicity.
  
  Rates ~ 20 kHz.

- Gamma - Hadron separation
  
  Proposed neural network approach:
  - Radial distribution of signal, steeper for photons.
  - Local fluctuations in the signal, greater for protons.
  - Yields $Q \sim 1.8$ retaining about 80% of Gammas.

- History:
  
  Tested 91% coverage of 51 m² February to May 1998.
  - 1.3 ns time resolution.
  - $\Delta_{EO} \sim 2°$ for 100 pad multiplicities.
  - Pb decreases $\Delta_{EO}$ from 8° to 5° for ~ 35 pad multiplicity.

  Construction began October 2000; now in progress.

  Expect data taking to begin in 2001 with 800m².

Conclusions

- Second generation of detectors coming into their own.

- Milagro
  - Milagrito shows method is understood, and already produced some interesting results.
  - $\gamma$/hadron separation in infancy, lots of room for improvement.
  - Many analyses under way.

- ARGO
  - Small scale detector behaved as expected.
  - Should provide interesting data from turn on.
  - More $\gamma$/hadron separation possibilities can be studied.

- Third generation detectors? Large area, high altitude, segmented, multiple layers, good timing.