Surveying the TeV Sky

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Outline:

Gamma Ray Astrophysics
Milagro Detections of New TeV Sources
High Altitude Water Cherenkov future
Producing Gamma Rays: Astrophysical Particle Accelerators

- Black Hole producing relativistic jet of particles
  - HST Image of M87 (1994)

- Spinning Neutron Star powering a relativistic wind
  - Chandra Image of Crab

- TeV image of Vela Jr. Supernova Remnant
  - HESS TeV + x-ray

- Binary Neutron Star Coalescing
  - Artist Conception of Short GRBs

- Massive Star Collapsing into a Black Hole
  - SuperComputer Calculation
High Energy Particle Astrophysics Questions

- What is the origin of cosmic rays?
  - Are the accelerators of hadrons different from electrons?
  - How high in energy can galactic sources produce particles?
  - What extragalactic sources can accelerate particles to even higher energies?

- How do astrophysical sources accelerate particles?
  - What is the role of the extreme magnetic and gravitational fields surrounding black holes and neutron stars?
  - How are particles accelerated within relativistic jets?
  - What interactions cause these particles to lose their energy?

- What constraints can we place on fundamental physics?
  - What is the dark matter?
  - What are the tightest constraints on Lorentz invariance?
  - Are there primordial black holes?
How do $\gamma$-rays answer these questions?

- Measure $\gamma$-ray flux due to cosmic-ray interactions
- Observe multiple $\gamma$-ray sources of different classes of astrophysical sources
- Distinguish hadronic from leptonic signatures in energy spectra and time variability
- Determine the highest energy particles accelerated in different types of sources
- Observe rapid variability to probe the closest regions to the black hole in active galactic nuclei
- Compare $\gamma$-ray images, spectra, and variability with those from other wavelengths
Comparison of Gamma-Ray Detectors

**Low Energy Threshold**
EGRET/GLAST

**High Sensitivity**
HESS, MAGIC, VERITAS

**Large Aperture/High Duty Cycle**
Milagro, Tibet, ARGO, HAWC

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**Space-based (Small Area)**
“Background Free”
Large Duty Cycle/Large Aperture

- Sky Survey $< 10$ GeV
- Transients (e.g. AGN, GRBs) $< 100$ GeV

**Large Effective Area**
Excellent Background Rejection
Low Duty Cycle/Small Aperture

- Studies of known sources
- Energy Spectra
- Spatial Morphology
- Surveys of limited regions of sky

**Moderate Area**
Good Background Rejection
Large Duty Cycle/Large Aperture

- Sky Survey 1–100 TeV
- Extended sources
- Unknown classes
- Transients
- Solar physics/space weather
Milagro Gamma Ray Observatory
@ 8600’ altitude near Los Alamos, NM

How Does Milagro Work?

- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water
- Reconstruct shower direction to ~0.5° from the time different PMTs are hit
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Field of view is ~2 sr and the average duty factor is >90%

Energy response if $\frac{dN}{dE} = k E^{-2.6}$

12 TeV

8 meters
Inside the Milagro Detector
Milagro’s Northern Hemisphere Map

- 6.5 years of observation
  - Last 2.5 years with ~2x better sensitivity due to outriggers
- Median Energy ~12 (20) TeV for dN/dE ∝ E^{-2.6} (E^{-2.3})
- Sensitivity varies by < factor of 2 across this map
- Previously known sources: Crab nebula 15σ, Mrk 421 7σ
- 3 New Sources > 5σ and 4 More Candidates
- Crosses are EGRET sources
- Contours are Molecular (Dame et al, 2001) and Atomic Hydrogen (Kalberla et al, 2005)
- TeV flux correlated with matter density
TeV Galactic Diffuse Spectrum

- Diffuse emission expected from cosmic ray interactions with matter and radiation
- Gamma rays probe cosmic rays outside the near Earth environment
- GeV gamma rays exceed predictions based on local cosmic ray flux
- Milagro’s TeV flux also exceeds predictions
- BUT are there unresolved sources???
>4.5σ Regions in the Galaxy

8 regions > 4.5σ (including Crab)

- Expect 0.04 spots >4.5σ in l∈ [30°,216°], b∈[-10°, 10°]

Distribution of Excesses in the Galactic Plane
Table 2. Galactic Sources and Source Candidates

<table>
<thead>
<tr>
<th>Object</th>
<th>Location (l, b)</th>
<th>Error(^a) (deg)</th>
<th>(\sigma) pre-trials</th>
<th>(\sigma) post-trials</th>
<th>Flux(^c) at 20 TeV (\times 10^{-15}) TeV(^{-1})cm(^{-2})s(^{-1})</th>
<th>Extent Diameter (deg)</th>
<th>Counterparts (References)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>184.5, −5.7</td>
<td>0.11</td>
<td>(15.0)</td>
<td>(14.3)</td>
<td>(10.9 \pm 1.2)</td>
<td>-</td>
<td>Crab</td>
</tr>
<tr>
<td>MGRO J2019+37</td>
<td>75.0, 0.2</td>
<td>0.19</td>
<td>(10.4)</td>
<td>(9.3)</td>
<td>(8.5) (8.7 \pm 1.4)</td>
<td>(1.1^\circ \pm 0.5^\circ)(^{d})</td>
<td>GEV J2020+3658, PWN G75.2+0.1, (1)</td>
</tr>
<tr>
<td>MGRO J1908+06</td>
<td>40.4, −1.0</td>
<td>0.24</td>
<td>(8.3)</td>
<td>(7.0)</td>
<td>(6.3) (8.8 \pm 2.4)</td>
<td>(&lt; 2.6^\circ(90%CL))</td>
<td>GEV J1907+0557, SNR G40.5−0.5</td>
</tr>
<tr>
<td>MGRO J2031+41</td>
<td>80.3, 1.1</td>
<td>0.47</td>
<td>(6.6)</td>
<td>(4.9)</td>
<td>(6.4) (9.8 \pm 2.9)</td>
<td>(3.0^\circ \pm 0.9^\circ)</td>
<td>GEV J2035+4214, TEV J2032+413 (2,3)</td>
</tr>
<tr>
<td>C1</td>
<td>77.5, −3.9</td>
<td>0.24</td>
<td>(5.8)</td>
<td>(5.8)</td>
<td>(3.4) (3.1 \pm 0.6)</td>
<td>(&lt; 2.0^\circ(90%CL))(^e)</td>
<td>-</td>
</tr>
<tr>
<td>C2</td>
<td>76.1, −1.7</td>
<td>(^e)</td>
<td>(5.1)</td>
<td>(2.8)</td>
<td>(4.5) (3.4 \pm 0.8)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C3</td>
<td>195.7, 4.1</td>
<td>0.40</td>
<td>(5.1)</td>
<td>(5.1)</td>
<td>(5.9) (6.9 \pm 1.6)</td>
<td>(2.8^\circ \pm 0.8^\circ)</td>
<td>Geminga</td>
</tr>
<tr>
<td>C4</td>
<td>105.8, 2.0</td>
<td>0.52</td>
<td>(5.0)</td>
<td>(2.6)</td>
<td>(6.3) (4.0 \pm 1.3)</td>
<td>(3.4^\circ \pm 1.7^\circ)</td>
<td>GEV J2227+6106, SNR G106.6+2.9</td>
</tr>
</tbody>
</table>

\(^a\)The table lists statistical errors only. The systematic pointing error is \(< 0.3^\circ\).

\(^b\)The post trials significances account for the trials incurred in searching the 3800 square degree region.

\(^c\)The table lists statistical errors only. The systematic flux error is 30%.

\(^d\)For this high significance detection, the extent was computed using only large events. See Abdo, A. et al. (2007) for details.

\(^e\)Gaussian fit of excess failed for this candidate.
EGRET 3EG Catalog Sources detected >100 MeV (36 in this region)

EGRET GEV Catalog Sources detected >1 GeV (14 in this region)
Crab: Electron Acceleration in Pulsar Wind Nebula

- TeV emission measures electron energies and magnetic fields
- Do other pulsar wind nebula accelerate protons as well?
  - Further Info Needed
    - Spatial Morphology from GeV to TeV
    - Spectra from GeV to TeV
Measuring Energy Spectrum with Milagro

- # of PMTs, zenith angle, & core location are correlated with energy
- Outrigger data (last 2.5 years) is needed to measure core location
- Crab spectrum agrees with atmospheric Cherenkov telescopes
- Still Working on Energy Spectrum of Other Sources
What’s Next? From Milagro to HAWC

High Altitude Water Cherenkov (HAWC)

- Increase Altitude to 4300 m from 2650 m
- Increase Area to 22000 m$^2$ from 4000 m$^2$
- Reuse Milagro PMTs and electronics
- HAWC $\sim$15x Sensitivity of Milagro
  - HAWC: Detect Crab in $\sim$ 1 day
  - Milagro: Detects Crab in $\sim$1/2 yr

HAWC Design:
Single layer of 900 PMTs (4 m depth vs Milagro’s 2 layers at 1.5 and 6 m) optically separated by curtains
Site Exploration (selection July 2007)

**Mexico**
- 2 hr drive from Puebla
- 4000 m elevation
- Site of the US/Mexico Large Millimeter Telescope

**Bolivia**
- 1/2 hr drive from LaPaz airport
- 4800 m elevation
- Near Mt. Chacaltaya Cosmic Ray Laboratory

**Tibet**
- 4300 m elevation
- Site of the Chinese/Italian ARGO detector
Difference between 2600m (Milagro) and 4300m (HAWC):
~ 6x number of particles
HAWC’s median trigger energy ~ 1 TeV vs Milagro’s ~ 4 TeV
Extensive Air Shower Detectors

Characteristic threshold determined by altitude and PMT density

Power Law: \( A \sim E^{2.6} \) as derivable from basic shower physics

Effective Area \( \approx \) Detector Area

HAWC Eff Area: \( \theta < 15, \Delta < 1.0, C > 5.0 \)
Gamma/Hadron Separation

Size of HAWC

Gammas

Size of Milagro deep layer

Protons

Energy Distribution at ground level

Larger Area implies better angular resolution + better cosmic ray background rejection
Lateral Distribution

- Protons have BROAD lateral distribution of muons
- Gammas have NARROW lateral distribution of electrons
Gamma-Ray Sensitivity

- **VERITAS, HESS, MAGIC, Whipple**
sensitivity in 50 hours,
(~0.2 sr/year)

- **GLAST** sensitivity in 1 year (4π sr)

- **HAWC, Milagro**, sensitivity in 1 year (2π sr)
Angular Resolution

Comparison of γ-ray sensitivity between the IACT and HAWC 2 year sky surveys as a function of source angular diameter. The HESS detected Galactic sources are shown.

Extended Source Sensitivity

HAWC Extended Source Sensitivity
Flaring Blazars detectable by HAWC at 5 Crab in 10 minutes

GrBs out to $z \sim 0.3$ (0.7) for $10^{-6}$ ($10^{-5}$) ergs/cm$^2$

Plus Solar Energetic Particles and ...

X-ray binary periods unobstructed by Moon or Sun
HAWC Complementary Science

- Complements TeV atmospheric Cherenkov telescopes
  - Identifies new and flaring sources for follow up observation of morphology and sub TeV spectra
  - Extends TeV spectra to higher energies

- Complements TeV neutrino observations
  - Identifies new and flaring TeV sources to improve the sensitivity and interpretation of blind searches

- Complements GeV All Sky Survey
  - Determines which of GLAST’s 1000s of sources extend to high energies
Joint Proposal to NSF and DoE High Energy Physics

Additional Collaborators – University of New Mexico, University of Utah and International Partners

Construction Budget

<table>
<thead>
<tr>
<th>Item</th>
<th>Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Preparation (Electricity, Internet, Water)</td>
<td>$0.6M</td>
</tr>
<tr>
<td>Pond &amp; Liner</td>
<td>$1.2M</td>
</tr>
<tr>
<td>Cover or Building</td>
<td>$2.0M</td>
</tr>
<tr>
<td>PMT Refurbishment &amp; Calibration System</td>
<td>$0.4M</td>
</tr>
<tr>
<td>Cabling, Electronics, Computers</td>
<td>$0.8M</td>
</tr>
<tr>
<td>Contingency 20%</td>
<td>$1.0 M</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>~$6 M</td>
</tr>
</tbody>
</table>

Milagro Construction Budget was $3.4M ($2.7M from NSF and $0.7M from DoE HEP)
Conclusion

- Milagro has demonstrated the power of the water Cherenkov technique
  - Detection of known sources, Crab Nebula and Mrk 421
  - Extended Detection of Galactic plane diffuse emission to TeV energies
  - Discovery of new Galactic TeV sources

- HAWC Builds on expertise of Milagro
  - Design improvements in Size, Altitude, Curtains . . .
  - 15x Milagro sensitivity

- INPAC may not have money, but political clout is also important
  - Endorsement of projects can help extract LANL funds
  - Encourage DoE and NSF to form Science Advisory Group (SAG) to review this field
TeV $\gamma$-rays: A New Window on the Sky