Milagro TeV
Galactic Unidentified Sources

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Milagro Gamma Ray Observatory
@ 8600’ altitude near Los Alamos, NM

The Instrument: Milagro

- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water
- Field of view is ~2 sr and the average duty factor is >90%
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Reconstruct shower direction to ~0.75° from the time different PMTs are hit
Inside the Milagro Detector
Array of 175 Outrigger Arrays

- Pond Area is 3600 m² operational in January 2001
- Outrigger Array area is ~ 30000 m² operational in June 2004
- Angular resolution improved from 0.75 to 0.4 deg
Background Rejection in Milagro

Hadronic showers contain penetrating component: $\mu$’s & hadrons
  – Cosmic-ray showers lead to clumpier bottom layer hit distributions
  – Gamma-ray showers give smooth hit distributions
Background Rejection Parameter

\[ A_4 = \frac{(f_{\text{Top}} + f_{\text{Out}}) \times n_{\text{Fit}}}{m_{\text{PE}}} \]

 mxPE: maximum # PEs in bottom layer PMT
 fTop: fraction of hit PMTs in Top layer
 fOut: fraction of hit PMTs in Outriggers
 nFit: # PMTs used in the angle reconstruction

S/B increases with increasing \( A_4 \) so analysis weights events by S/B as determined by the \( A_4 \) value of the event

Improves sensitivity by \( \sim 2 \times \)
Milagro Survey

- 6.5 year data set (July 2000-January 2007)
- Weighted analysis using A4 parameter
- Events smoothed by PSF
- Energy range: 4-150 TeV, Median 20 TeV
- Crab nebula 15 $\sigma$

Milagro sees the Galactic plane from longitude ~30° to ~220°
Milagro has discovered 3 new sources & 4 candidate sources in the Galaxy.
5/7 of these TeV sources have GeV counterparts (only 13 GeV counterparts in this region - excluding Crab)
- Probability = $3 \times 10^{-6}$

Boxes mark sources from EGRET 3EG catalog

• 80% of the Crab flux
• 87 hr observation by HEGRA
• upper limit of 2.6% of the Crab flux (700 GeV)
• could be both extended and point source (diam. < 2.6 deg, HESS)
Geminga: brightest EGRET source in the northern hemisphere sky
- extended: diam. 2.8 +/- 0.8 (corr. to 8 pc)
- significance increased for larger bin
- upper limits on TeV flux (100 mcrab) at lower energies and based on point source assumption


- least significant source but elongated
- significance increases with larger bin
- counterparts: GeV J2227+6106, SNR G106.6+2.9, BOOMERANG PWN
The Cygnus Region

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  - no counterparts
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- MGRO J2019+37: 10.4σ
  - Extended source 1.1° ± 0.5° (top hat dia.)
  - Possible Counterparts
    - GeV J2020+3658, PWN G75.2+0.1

The Cygnus Region

C1 J2044+36: 5.5σ pre-trials – no counterparts ≤ 2.0σ

C2 J2031+33: 5.3σ pre-trials – possible extension of MGRO J2019+37 – possible fluctuation of MGRO J2019 tail & diffuse emission & background

MGRO J2019+37: 10.9σ – Extended source 1.1° ± 0.5° (top hat dia.) – Possible Counterparts

Gev J2020+3658, PWN G75.2+0.1

MGRO J2031+41: 6.6σ (54.9σ post-trials) – Possible Counterparts:

3EG J2033+4118, GEV J2035+4214

TEV J2032+413 (⅓ of Milagro flux) – 3.0° ± 0.9° (top hat dia.)

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Tibet ASγ preliminary detections of 3 Milagro sources

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Remarks about source fitting

+ offset/base
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129 EGRET sources (>100 MeV) in Milagro fov

- 20 of the EGRET sources are > 2 sigma in Milagro map
Flat Spectrum EGRET sources
Some Steeper Spectrum Sources also break
TeV Diffuse Emission from the Galactic Plane

Previous measurements

- **EGRET**: EGRET observations to 20 GeV indicate a “GeV excess”, harder γ-ray spectrum than predicted on the basis of local cosmic-ray spectrum and intensity measurements (Hunter et al. 1997)

- **Milagro**: >3.5 TeV, 40<l<100 → indication of “TeV excess”; @ 12 TeV, Cygnus region → 3 to 7 times higher then cosmic-propagation model GALPROP (Atkins et al. 2005, Abdo et al. 2007)

- **HESS**: Galactic Center Ridge, diffuse emission correlated with giant molecular clouds, also harder spectrum, enhancement by a factor 3-9 above 1 TeV (Aharoni...
Diffuse Emission

A4-weighted sky map

Flux profiles ← Source subtraction ← + offset/base
Diffuse Emission

The Diffuse Galactic Plane
TeV Diffuse Emission from the Galactic Plane with Milagro

Comparison with model predictions

- Compare flux and longitudinal and latitudinal emission profiles to model predictions
- We used GALPROP for the comparison (Strong et al. 2004)
- GALPROP is a model calculating cosmic-ray propagation numerically
- Emissivities are calculated based on propagated CR spectra and gas and radiation densities in the Galaxy
- Two versions: “conventional” → reproduces local CR measurements; “optimized” → tuned to match EGRET data
1. Cygnus region: Flux observation exceeds model predictions by a factor of two
2. Flux ratio Inner Galaxy to Cygnus region: data: $1.1 \pm 0.2$ (stat.) ; model: 2.0
The Model:

- Inverse Compton target photons extend to higher latitudes
- Pion decay due to interactions with matter at low latitudes
- Inverse Compton flux increases towards inner Galaxy
Flux Profiles: II Galactic Latitude

Compare the shape:
One test: perform Gaussian fit and compare FWHM

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>GALPROP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Galaxy</td>
<td>$2.1\pm0.7$</td>
<td>4.1</td>
</tr>
<tr>
<td>Cygnus</td>
<td>$4.7\pm0.5$</td>
<td>6.9</td>
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</tbody>
</table>
Flux Profiles:
II Galactic Latitude

Compare the shape:
Better test: perform a $\chi^2$ fit of 2 components predicted by GALPROP to data

Prob.
Inner Galaxy: $5.7 \times 10^{-1}$
Cygnus: $1.1 \times 10^{-4}$

Best fit in Cygnus: Increase pion contribution by a factor of ~7
Spectrum Inner Galaxy

Average Electron Spectrum (GALPROP)
Spectrum
Cygnus Region

- region of intense star formation activity
- Cygnus OB2, VLA SNR detection, XMM extended x-ray source observation, TeV 2032+4130, MGRO J2031+41
- GALPROP: again dominant IC contribution, but measured profile agrees better with pion prediction of GALPROP
- remaining excess can be explained with only a few strong young proton accelerators, where the protons interact with clouds at only 100 pc distance from the source (estimation based on Gabici & Ahahronian et al. 2007)
The future: HAWC

- Increase Altitude to 4100 m from 2650 m
- Increase Area to 22,000 m² from 4,000 m² (top layer) or 2,200 m² (bottom layer)
- Reuse 900 Milagro PMTs and front end electronics
- Cost $7.4M
- HAWC 10 – 15 x Sensitivity of Milagro: Detect Crab in ~ 1 day (5σ)

HAWC Tank Array in GEANT 4
HAWC Collaboration

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HAWC’s Field of View

1 yr Survey Sensitivity (mCrab)

Declination

= 2.6 \pi \text{ sr}

= 1.8 \pi \text{ sr}
Conclusion

• Milagro GP survey:
  – 8 sources, 7 new
  – 4 high significance and 2 low significance coincide with EGRET GeV sources
  – 4 of these six sources appear extended
  – Connecting spectrum between EGRET GeV and Milagro TeV: -2.3 (except Geminga)
  – Four associated with PWN, 1 SNR
  – Diffuse emission excess in Cygnus: a few young accelerators
  – Need to be careful when disentangle diffuse and source emission