Spectrum and Morphology of Milagro Sources

VERITAS Galactic Workshop

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Milagro Detector

- Water Cherenkov Detector
- 2640m (8640’') elevation
- 898 photomultiplier tubes
  - 450 in top layer in pond
  - 273 in bottom layer in pond
  - 175 water tank outriggers
- Pond Area is 3600 m$^2$
  - Operational in January 2001
- Outrigger Array area is ~ 30000 m$^2$
  - Operational in June 2004
- Shutdown June 2008
- 10x the data rate as Tibet.
Milagro Collaboration

Trigger: ~60 PMTs hit within 180ns window

Event Rate ~1700 Hz with 8% dead time. Due almost entirely to CR p(70%) He(25%) C, O, Ne, Mg, Si, Fe(5%)

Operational for 7 years, 4 years with outrigger array.

>90% on-time

Online reconstruction only, “raw” data not recorded.

Angular resolution <1°

>300 x 10⁹ events logged.
14 TeV BSL associations including the Crab
• Most Significant northern Fermi source
• Old (300 kyr) and nearby (169 pc)
• 3.5σ at the location of Geminga
• 6.3σ when assuming 1° extended source
• Fitted FWHM 2.6° extent, consistent with IACT observations of more distant PWN
- Associated with MGRO J1908+06, discovered by Milagro and confirmed by HESS and VERITAS (left)
- J1900..0+0356 has no known association (right)
- Milagro detects an excess of 7.4σ and 3.6σ respectively at the location of the Fermi sources.
- VERITAS detection and spectrum
• BSL source associated with previously reported MGRO J2019+37
• Most significant source in the Milagro data set apart from the crab.
• Young pulsar (17.2 kyr) discovered by AGILE
• Milagro detects a 12.4σ excess at the position of the Fermi source
• ~2 sigma broader than point source
• J2021.5+4026 LAT discovered pulsar associated with gamma-Cygni SNR.
• J2032.2+4122 is a LAT discovered pulsar associated with HEGRA, Milagro and MAGIC TeV detections.
• Milagro observers excesses of 4.2σ and 7.6σ respectively at the positions of the Fermi sources.
• “Boomerang” PWN
• Associated with radio pulsar J2229+6114
• Milagro detects a 6.6σ excess at the location of the Fermi source.
• Noted excess was very extended (4 deg)
• New Fermi pulsar (Science last Summer) located in the southern ‘tail’ with 4.7σ in Milagro data.
• VERITAS source
Introduction of Energy Parameter

\[ FrASOR = \frac{N_{hit}^{AS}}{N_{live}^{AS}} + \frac{N_{hit}^{OR}}{N_{live}^{OR}} \]
Energy Dependence of FrASOR
Fitting Procedure

\[ \text{Flux} = I_0 \left( \frac{E}{\text{TeV}} \right)^{-\alpha} e^{-\left( \frac{E}{E_c} \right)} \]

Perform fit in 'Frasor' space, not energy space.

Minimize \( \chi^2(I_0, \alpha, E_c) = \sum (F_r(I_0, \alpha, E_c) - F_{\text{measured}})^2 / \sigma^2 \)

Method extensively tested with fits to the hadronic background spectrum
Spectrum of the Crab

Softer than IACT spectra (\( \alpha_{\text{IACT}} \approx 2.6 \))

Fit Results: (no cutoff)

\[
\begin{align*}
I_0 &= 6.6 \ [5.0,8.0] \times 10^{-7} \text{ /s/m}^2/\text{TeV} \\
\alpha &= 2.95 \ [2.85,3.03] \\
\chi^2 &= 28.3 \ (25 \ \text{dof})
\end{align*}
\]

Fit Results: (3-parameter)

\[
\begin{align*}
I_0 &= 5.2 \ [2.0,8.0] \times 10^{-7} \text{ /s/m}^2/\text{TeV} \\
\alpha &= 2.75 \ [2.22,3.03] \\
\Gamma &= 71 \ [22,\text{inf}] \\
\chi^2 &= 27.1 \ (24 \ \text{DOF})
\end{align*}
\]

Energy reach from \( \sim 3\text{TeV} \) to \( >100 \text{ TeV} \)

Peak sensitivity for \( E^{-2} \) source at \( \sim 100 \text{ TeV} \)
Mrk 421

Reweighed to remove emphasis on high energy events

Fit Results: (3-parameter)
Io = 5.2 [1.9, 14.0] \times 10^{-7} \text{ s/m}^2/\text{TeV}
\alpha = 1.90 [1.50, 3.5]
Ec = 2.5 [1.4, 20]
\chi^2 = 33.5 (24 DOF)

Fit Results: Fix spectral index at 2.1 (2-parameter)
Io = 5.4 [3.0, 10.1] x 10^{-7} \text{ s/m}^2/\text{TeV}
Ec = 2.8 [1.8, 4.0] \text{ TeV}
\chi^2 = 28.3 (25 dof)
MGRO J1908+06

If HESS accurately measures spectrum at low energies, a cutoff is required.

Fit Results: (no cutoff)
\[ I_0 = 6.6 \times 10^{-7} \text{ m}^2/\text{TeV} \]
\[ \alpha = 3.00 \text{ [2.8,3.2]} \]
\[ \chi^2 = 29.3 \text{ (25 DOF)} \]

Fit Results: (3-parameter)
\[ I_0 = 0.62 \times 10^{-7} \text{ m}^2/\text{TeV} \]
\[ \alpha = 1.50 \text{ [1.50,2.65]} \]
\[ E_c = 14 \text{ [10,50] TeV} \]
\[ \chi^2 = 22.1 \text{ (24 DOF)} \]

Fit Results: (hold \( \alpha = 2.1 \))
\[ I_0 = 2.1 \times 10^{-7} \text{ m}^2/\text{TeV} \]
\[ E_c = 14 \text{ [10,40] TeV} \]
\[ \chi^2 = 23.3 \text{ (25 DOF)} \]
In Milagro J2019+37 is 700 mCrab

The flux in $\nu / s > 200 \text{ GeV}$ is 95mCrab

HESS Crab fit

Cutoff $< 56 \text{ TeV}$

Cutoff $< 80 \text{ TeV}$

If the spectrum is hard (2.1), a cutoff is required.

Fit Results: (no cutoff)

$Io = 1.74 [1.10-2.50] \times 10^{-7} \text{ /s/m}^2/\text{TeV}$

$\alpha = 2.62 [2.50-2.75]$

$\chi^2 = 31.7 (25 \text{ DOF})$

Fit Results: (3-parameter)

$Io = 0.54 [0.20,1.82] \times 10^{-7} \text{ /s/m}^2/\text{TeV}$

$\alpha = 1.83 [1.50,2.55]$

$Ec = 22 [12,177] \text{ TeV}$

$\chi^2 = 26.9 (24 \text{ DOF})$

Fit Results: (hold $\alpha = 2.1$)

$Io = 0.87 [0.64,1.1] \times 10^{-7} \text{ /s/m}^2/\text{TeV}$

$Ec = 31 (25,44) \text{ TeV}$

$\chi^2 = 27.3 (25 \text{ DOF})$
MGRO J2031+41/TeV 2032+41

Fit Results: (no cutoff)
Io = 2.6 [1.3,3.6] x 10^{-7} /s/m^2/TeV
\alpha = 3.02 [2.80,3.20]
\chi^2 = 24.2 (25 DOF)

Fit Results: (3-parameter)
Io = 0.42 (0.20,2.40) x 10^{-7} /s/m^2/TeV
\alpha = 1.53 [1.50,2.83]
Ec= 9 [5.6,56] TeV
\chi^2 = 18.6 (24 DOF)

Fit Results: (hold \alpha=2.1)
Io = 0.92 [0.58,1.50] x 10^{-7} /s/m^2/TeV
Ec= 14 (9,20) TeV
\chi^2 = 18.6 (25 DOF)
Boomerang - MGRO J2229+61, 0FGL J2229+6114

Fit Results: (no cutoff)
Io = 4.0 [1.7,7.1] x 10^{-7} /s/m^2/TeV
α = 3.10 [2.83,3.38]
\( \chi^2 = 14.4 \) (25 DOF)

Fit Results: (3-parameter)
Io = 2.68 (0.18,7.72) x 10^{-7} /s/m^2/TeV
α = 2.70 (1.50,3.42)
Γ = 45 (6,inf) TeV
\( \chi^2 = 13.9 \) (24 DOF)

Fit Results: (hold α=2.1)
Io = 1.28 [0.55,2.50] x 10^{-7} /s/m^2/TeV
Ec = 14 (8,25) TeV
\( \chi^2 = 18.6 \) (25 DOF)
The HAWC Observatory
The HAWC Collaboration

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HAWC (High Energy Water Cherenkov) Observatory

HAWC will be ~15x more sensitive than Milagro to a like spectrum
HAWC Baseline Design -
• 300 7.3m diameter, 4.3m tall water tanks.
• 150000 liters/tank
• Each tank has 3 upward facing PMT 4.0m below the surface of the water.
• Tanks densely packed over 150m x 150m region (~60% coverage)
• Reuse Milagro analog electronics and PMTs
• Readout with VME multi-hit TDCs.
• Time-over-threshold for 5 decade pulse amplitude scale (0.1-10^4 PEs)