Prospects for Observations of Very Extended and Diffuse Sources with VERITAS

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Angular resolution will be more consistent than ever before in a large part of the gamma-ray energy band: joint analysis has real potential.

- **Fermi**: ~0.5° at 1GeV to <0.1° (>10 GeV)
- **VERITAS**: ~0.15° at 150GeV to <0.1° (>1 TeV)
- **HAWC**: ~0.5° at 1TeV to <0.2° (>10 TeV)
Extended and Diffuse Sources

VERITAS has observed several very extended and/or diffuse sources:

- Cygnus Cocoon
- Geminga (PWN)
- Cisne (complex overlapping emission)
- Gamma Cygni (supernova remnant)
- Galactic Center

Other sources or potential sources of very extended or diffuse emission include:

- Galactic diffuse emission
- Galaxy clusters (extragalactic)
**Cygnus Cocoon**

Observations by *Fermi-LAT* since the Cygnus survey reveal a 4 square degree source of high energy emission.

Freshly accelerated cosmic rays trapped in cavity: “cocoon”

Protons or electrons?

Escaped from nearby sources?
\textbf{Which?}

Infrared image with gamma-ray emission overlay (purple)

Credit: NASA/IPAC/MSX

Credit: NASA/DOE/LAT/MSX/IPAC
Geminga: Positron Excess?

A handful of local (d < 1 kpc) pulsars is all we need to explain the positron anomaly.

There could even (likely?) be only one source: Geminga (Yuksel et al 2009, Serpico 2012, di Mauro et al 2014)

~340 kyr old X-ray and gamma-ray pulsar
X-ray PWN, possible TeV PWN at vastly different scales
We could live in halo of long-escaped e+/e-
Moderately Extended Source Detection

Currently, moderately extended sources are detected in a similar way to point sources using the ‘Ring Background Method’ (RBM)

- Large integration region (typically ~0.25 degrees)
- suitably chosen background region.

Alright for moderately extended sources, but not for very extended sources.
Very Extended Source Detection: On-Off

“On-Off” observations are taken in the following manner:

● **On** - Observations on your source of interest
● **Off** - Observations on a blank sky field. The altitude and azimuth of ‘off’ observations are chosen such that they match as closely as possible to the ‘on’ observations.

‘Off’ observations are used for background estimation in the ‘on’ observations.

Pros:
● Better background estimation over RBM for very extended sources.

Cons:
● Must dedicate 1/2 of observing time to ‘blank field’ observations.
● Background in ‘on’ and ‘off’ fields may not be entirely similar.
Maximum Likelihood Method

Maximizes, with respect to a set of free parameters, the “likelihood” that a particular dataset originates from a particular model.

\[
l(s) = \prod_{i=1}^{N} p(x_i|s) \tag{s) are a set of free parameters}
\]

Parameters can represent physical quantities (spectral index, flux normalization, source radius)

In practice, typically minimize \( \log(l(s)) \), which causes the product to become a sum

Utilizing Wilks’ Theorem we formulate a test-statistic by computing the likelihood ratio between a “null” model and a “test” model.

\[
TS = -2 \cdot \ln \left( \frac{l_{null}}{l_{test}} \right)
\]

Assuming TS is normally distributed, we can use it to approximate significance
Probability Density Functions

- Probability density function (PDF) gives relative likelihood that a random variable takes on a given value.

- Multi-dimensional PDFs: set of random variables.

- Models convolved with response functions = PDFs.

- When random variables in multi-dimensional PDF uncorrelated, can treat as product of lower-dimensional PDFs.
Constructing PDFs I: Spatial Models

Spatial models represent distribution of photons projected on the sky.

**Background Model**
Polynomial fit to radial acceptance curve.
(response function convolved with trivial “flat” background model)

**Source Model**
Intrinsic source model:
- weighted by gamma-ray acceptance
  - response function I (effective area) x spectrum (parametric dependence of PDF)
- convolved with PSF (response function II)

*Work ongoing to better characterize response functions*
Constructing PDFs II: MSW Models

To improve sensitivity to large extended sources we include mean scaled width as a third dimension.

MSW models are interpolated in zenith angle

\[ \text{PDF}_{\text{MSW}} = f(\text{msw} | \text{zenith}) \]

Background Model
Derived from Dwarf Spheroidal
and weak AGN data *(using a 0.4 degree source exclusion)*

Source Model
Derived from simulations at varying zenith angle.
Constructing PDFs: Combining Models

Models broken up into bins of energy, by season (winter/summer), observing epoch, zenith angle, and telescope multiplicity.

Spatial and MSW models are combined in the following way (for each pointing):

\[ F(x, y, w) = N_{src}(f_0, \Gamma) \cdot S_{src}(x, y) \cdot MSW_{src}(w) + N_{bkgd} \cdot S_{bkgd}(x, y) \cdot MSW_{bkgd}(w) \]

where:

- \( N \) = total number of events in a particular observation (dependent on spectral parameters)
- \( x, y \) = spatial coordinates
- \( w \) = MSW coordinate
Tools: Toy MC Generation

Taking our full model as input, we can generate Toy MC events to see what an actual observation might look like.

These Toy MC can also be used to determine how our calculated TS relates to significance.
Diagnostic Tools: Residual Maps

In addition to saving all distributions used for generating our models we also generate and save the following:

**Spatial residual maps**
- Incorrect spatial model
  (ex: incorrect PSF width)
- Incorrect source position
  (ex: source offset from nominal position)
- Unaccounted for emission
  (ex: weak source in thefov)

**Toy MC residual map** showing result of a perfect model

**Crab residual map** showing results of using a large (0.08° Gaussian) source model
(data-model) / livetime

**MSW residual maps**
- Incorrect MSW models
- Incorrect signal fraction
3D MLM: Point Source Example

Approximately 56 runs of Crab data taken between summer 2009 - winter 2012. Results of this analysis:

- MSW models need improvement
  - Solution: include seasonal dependence into models
- Spatial PDF needs improvement (Pure Gaussian doesn’t work)

livetime corrected excess map
(data-model)/livetime
3D MLM: Geminga Example

Geminga is a potential candidate for detection.
- predict 27% Crab flux between 500 GeV - 1 TeV
- Large extent ~ 2°

Notes:
1. Can detect emission filling nearly the entire field of view.
2. Such a large source would potentially require more observations to expose the full extent of the source.
Source Model Improvements

Following the prescription of Mattox et al. (1996) we take into account

- VERITAS PSF (in true energy)
- Source Spectrum (allow fitting for spectral index)
- Energy Resolution
- Effective Areas

\[
PSF(\theta) = \frac{1}{N} \int_{E_{\text{min}}}^{E_{\text{max}}} \int_{0}^{\infty} PSF(\theta, E') \cdot E'^{-\epsilon} \cdot R(E', E) \cdot A(\theta', E', ...) \cdot dE' \cdot dE
\]

‘\(E_{\text{min}}\)’ and ‘\(E_{\text{max}}\)’ represent energy range covered by a particular bin in reconstructed energy.

To determine the energy dependent PSF (based on our cuts) we simulate many particle showers at fixed energies.

Appears best described by KLng function

This work is ongoing
3D MLM: Cygnus Region

- 3D MLM produces clean detections of cocoon, gamma Cygni, TeV J2032+4130, VER J2019+407
- $\sqrt{TS} > 45$, 8, and 5 respectively.
- VER J2019+407 becomes marginal ($TS \sim 9$) once SNR disk emission accounted for...which is exactly what happened to Fermi
Improving Extended Source Models

Currently modeling extended sources using a broad Gaussian, but ...

A more accurate method would derive our extended model from

- *Fermi* / HAWC maps allowing comparison of source morphology at different energies.
- CO maps improving background emission modeling along the galactic plane.

[CLEARLY NOT GAUSSIAN!]
Summary

The VERITAS maximum likelihood is in development

- No new data being processed through MLM
- Promising first pass Toy MC results
- Single coherent method to detect and study point sources to very extended sources.

Development of diagnostic tools (so we can be sure that we get it right)

- Toy MC for source studies and
- Residual maps to evaluate models and fitted parameters

Future goals

- Likelihood a natural vehicle for joint analysis across multiple instruments (Fermi / HAWC)