Analyzing VHE GRBs with VERITAS

Miles Garcia, Nevis Labs REU Summer 2021
Outline

Introduction
- Gamma Rays
- Sources of Gamma Rays & GRBs
- IACTs & VERITAS

GRB Analysis
- Selecting GRBs for Analysis
- VEGAS Analysis Process
- VEGAS Results
- Calculating Upper Limits

VEGAS Testing
- Process
- Results

Conclusions and The Future
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Conclusions and The Future
Energy Units: $E=nh$ (photons), $E=mc^2$ (massive particles)! For reference, proton at rest $\sim 1$ GeV
Further categorization of gamma rays:
- Gamma rays cover 8 orders of magnitude...
  MeV = $10^6$ eV
- Low Energy (LE): 0.1 - 100 MeV
- High Energy (HE): 0.1 - 100 GeV
  GeV = $10^9$ eV
- Very High Energy (VHE): 0.1 - 100 TeV
  TeV = $10^{12}$ eV
- And Beyond...

Particle Accelerators: Earth vs Space
- On Earth, the LHC can accelerate protons to $\sim 10^{12}$ eV
- Astrophysical accelerators can send protons to $\sim 10^{20}$ eV!
- Gamma rays come from the most energetic events in our universe...
Sources of Gamma Rays

Active Galactic Nuclei
Binary Neutron Stars
Gamma Ray Bursts
Sources of Gamma Rays: Emission Mechanisms

- **Synchrotron Emission**
  - [Link](http://www.irinafirel.com/~ddallaca/L04_Synch.pdf)

- **Inverse Compton Scattering**
  - ![Inverse Compton Scattering](https://upload.wikimedia.org/wikipedia/commons/thumb/1/1e/Bremsstrahlung.svg/1200px-Bremsstrahlung.svg.png)

- **Bremsstrahlung**
  - ![Bremsstrahlung](https://upload.wikimedia.org/wikipedia/commons/thumb/1/1e/Bremsstrahlung.svg/1200px-Bremsstrahlung.svg.png)

High energy e- initially e- loses energy
Why Study Gamma Rays?

- Highest energy events emit gamma rays
- We can use gamma rays to better understand the phenomena that emit them
- Different emission mechanisms release different energy gamma rays-- not simple
- Reconstruct and model source physics from the gamma rays it releases
- Multi-wavelength astronomy: looking at photons emitted by source across EM spectrum

Why Study Gamma Rays?

- Cosmic rays (relativistic charged particles) emitted in same place as gamma rays, and we want to learn about their acceleration mechanisms
- Photons have no charge. They are not deflected by magnetic fields, so gamma rays can be traced back to their source, unlike cosmic rays.
- So gamma rays help us study cosmic rays indirectly
- Multi-Messenger Astronomy! (Neutrinos, Gravitational Waves...)

https://astro.desy.de/sites2009/site_astro/content/e233776/e233884/e234019/follow_up_eng.png
Gamma Ray Bursts

- Most energetic events in the universe → highest energy gamma rays
- 2 Types: Short (<1 sec), Long (>1 sec): different emission and causes
- Mixture of processes (beyond synchrotron peak)
- 2 Phases: Prompt Emission (< 1ms - ~100s, highest energy photons) + Afterglow (longer, wider range of lower energy photons)
- Extragalactic only
Space Telescopes and Ground Telescopes

https://upload.wikimedia.org/wikipedia/commons/thumb/6/6f/Fermi_Gamma-ray_Space_Telescope_logo.svg/180px-Fermi_Gamma-ray_Space_Telescope_logo.svg.png

https://upload.wikimedia.org/wikipedia/commons/thumb/b/b7/Fermi_Gamma-ray_Space_Telescope_spacecraft_model.png/300px-Fermi_Gamma-ray_Space_Telescope_spacecraft_model.png

Imaging Atmospheric Cherenkov Telescopes (IACTs)

https://veritas.sao.arizona.edu/
https://www.mpi-hd.mpg.de/hfm/HESS/
http://www.magic.iac.es/
https://www.cta-observatory.org/
The Imaging Atmospheric Cherenkov Technique

Geometry: Direction
Intensity: Energy
Shape: Signal vs. Noise


https://www.researchgate.net/profile/Alicia-Lopez-Oramas/publication/2753129
291/figure/fig3/AS:614365657063429@1523487595/Left-Electromagnetic-air-shower-generated-by-a-primary-g-ray-and-purely-composed-of.png

https://media.springernature.com/original/springer-static/image/chp%3A10.1007%2F978-3-030-
24894-8_3/MediaObjects/483406_1_En_3_Fig6_HTML.png

https://i.ytimg.com/vi/j-BBzWlOai0/maxresdefault.jpg

https://i.ytimg.com/vi/j-BBzWlOai0/maxresdefault.jpg
- 4x 12-m diameter telescopes with 3.5 degree FOV
- Each telescope has 350 hexagonal mirrors to focus incident light onto camera
- Camera consists of 499 “pixels” = photomultiplier tubes
- Energy range: 100 GeV - 30 TeV
- Operating with all telescopes since 2007!
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Conclusions and The Future
Motivation

LAT GRBs Observed Per Year

Swift GRBs Observed Per Year

GRB Observations Per Year
First Step: Which GRBs Do We Analyze?

- Don’t want to blindly pick random GRBs-- bad use of time, less chance of result!
- Want to pick GRBs that have characteristics which give higher likelihood of detection

**Solution: Weight Function**

\[ W = e^{-\tau(z, E_{\text{th}}(\theta))} / t_{\text{obs}} \]

\( \tau \): Absorption due to Extragalactic Background Light (EBL)-- light from the early universe that causes pair production

- Function of redshift \((z)\), Energy threshold of the observation \((E_{\text{th}})\), which comes from zenith angle, \(\theta\), of the telescope

\( t_{\text{obs}} \): Delay between burst and observation start

---

VHE GRBs that actually got detected probably have strong weights... use them as reference point for VERITAS weights

<table>
<thead>
<tr>
<th>VERITAS GRBs</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>150120A</td>
<td>8.17E-04</td>
</tr>
<tr>
<td>150423A</td>
<td>7.86E-03</td>
</tr>
<tr>
<td>160509A</td>
<td>3.01E-08</td>
</tr>
<tr>
<td>170428A</td>
<td>6.63E-06</td>
</tr>
<tr>
<td>170519A</td>
<td>1.80E-06</td>
</tr>
<tr>
<td>201216C</td>
<td>2.77E-05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tevcat GRBs</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>180720B</td>
<td>1.98E-05</td>
</tr>
<tr>
<td>190114C</td>
<td>4.10E-03</td>
</tr>
<tr>
<td>190829A</td>
<td>5.97E-05</td>
</tr>
<tr>
<td>201216C</td>
<td>5.94E-05</td>
</tr>
</tbody>
</table>
VEGAS Analysis

- Takes in: list of VERITAS runs, configuration settings set up by user
- Produces: Plots, upper limit results, significance results
- 6 stages
- Configuration: Analysis methods (ITM, TDRBM), Time cuts, and lots of very specific configurable settings

<table>
<thead>
<tr>
<th>GRB</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Run 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>150120A</td>
<td>76029</td>
<td>76030</td>
<td>76031</td>
<td>76032</td>
<td>76034</td>
<td></td>
</tr>
<tr>
<td>150423A</td>
<td>77424 A(w)</td>
<td>77425</td>
<td>77426</td>
<td>77427</td>
<td>77428</td>
<td></td>
</tr>
<tr>
<td>160509A</td>
<td>82004 p(w)</td>
<td>82005</td>
<td>82007 A(h)</td>
<td>82008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>170428A</td>
<td>85976</td>
<td>85977 X(w)</td>
<td>85978 X(w)</td>
<td>85979 p(w)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>170519A</td>
<td>86207 A(w)</td>
<td>86208</td>
<td>86209</td>
<td>86210 A(w)</td>
<td>86211 A(w)</td>
<td>86212</td>
</tr>
<tr>
<td>201216C</td>
<td>97164</td>
<td>97165</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Runs & Info

Run Status(Reason)
Status - X = do_not_use;
A = needs_adjustments;
p = minor_problems;
Reason - w = weather; h = hardware
VEGAS Results Template-- Crab Nebula

Sign Distr for all bins

Sign Distr Minus Source Exclusions

Sign Distr Minus Star Exclusions

Sign Distr Minus All Exclusions

Dec [deg]

RA [deg]

Significance [I/E]

Excess [counts]
VEGAS Results: GRB201216C

Standard Analysis

ITM Analysis
Standard Analysis

Source Location | Max Sig Location
--- | ---
[34m+++ RA (deg) : 16.3703 | 16.4576
[34m+++ Dec (deg) : 16.5161 | 15.7362
[34m+++ ON counts : 148 | 150
[34m+++ OFF counts : 1118 | 658
[34m+++ EXCESS counts : 10.5153 | 50.2479
[34m+++ Alpha param. : 0.122974 | 0.151599
[34m+++ SIGNIFICANCE : 0.834667 | 4.31597[34m sigma
[34m+++ EXPOSURE (min): 51.0314
[34m+++ Integral acc. : 0.097303 | 0.0817669
[34m+++ RATE (gam/min): 0.206056 | 0.984646
[34m+++ : +/- 0.251641 | +/- 0.251805
[34m+++ Backgrd RATE : 2.69412 | 1.95472
[34m+++ (BG/min): +/- 0.0805741 | +/- 0.0762029
[34m+++ Peak significance is 0.7845 deg from Source location.

Wobble Analysis Result for VEGAS version: heads/v2_5_7
Total On events : 134 Total Off events : 785
Total Exposure Time: 51.03144 Alpha : 0.1538462 (from rel exposure)
There are mixed alphas :0.1428571 0.1666667
Significance : 1.09861
Rate_Gamma = 0.259267 +/- 0.2420532
Rate_Bg = 2.360356
Rate_Bg / Rate_Gamma^2 = 35.11422

ITM Analysis

Source Location | Max Sig Location
--- | ---
[34m+++ RA (deg) : 16.3703 | 16.7276
[34m+++ Dec (deg) : 16.5161 | 16.8458
[34m+++ ON counts : 45 | 66
[34m+++ OFF counts : 1081 | 855
[34m+++ EXCESS counts : 1.55841 | 25.7868
[34m+++ Alpha param. : 0.0401865 | 0.047033
[34m+++ Alpha unc. : 0.00307855 | 0.00361349
[34m+++ SIGNIFICANCE : 0.206343 | 3.23179[34m sigma
[34m+++ EXPOSURE (min): 51.0314
[34m+++ Integral acc. : 0.0315369 | 0.0307187
[34m+++ RATE (gam/min): 0.0305383 | 0.505312
[34m+++ : +/- 0.133978 | +/- 0.161462
[34m+++ Backgrd RATE : 0.851271 | 0.788008
[34m+++ (BG/min): +/- 0.0258914 | +/- 0.0269493
[34m+++ Peak significance is 0.4752 deg from Source location.

Wobble Analysis Result for VEGAS version: heads/v2_5_7
Total On events : 42 Total Off events : 425
Total Exposure Time: 51.03144 Alpha : 0.09090909 (from rel exposure)
0.09090909
Significance : 0.510239
Rate_Gamma = 0.06591303 +/- 0.1321987
Rate_Bg = 0.7571091
Rate_Bg / Rate_Gamma^2 = 174.2673
### Standard Analysis

<table>
<thead>
<tr>
<th>Source Location</th>
<th>Max Sig Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (deg) : 330.078</td>
<td>329.461</td>
</tr>
<tr>
<td>Dec (deg) : 26.9158</td>
<td>25.3982</td>
</tr>
<tr>
<td>ON counts : 33</td>
<td>22</td>
</tr>
<tr>
<td>OFF counts : 275</td>
<td>82</td>
</tr>
<tr>
<td>EXCESS counts : 1.65286</td>
<td>14.4898</td>
</tr>
<tr>
<td>Alpha param. : 0.11399</td>
<td>0.0915874</td>
</tr>
<tr>
<td>SIGNIFICANCE : 0.27705</td>
<td>4.0103 (34m sigma)</td>
</tr>
<tr>
<td>EXPOSURE (min): 97.4386</td>
<td></td>
</tr>
<tr>
<td>Integral acc. : 0.0919161</td>
<td>0.0233606</td>
</tr>
<tr>
<td>RATE (gam/min): 0.0169631</td>
<td>0.148707</td>
</tr>
<tr>
<td>: +/- 0.0620656</td>
<td>+/- 0.0488389</td>
</tr>
<tr>
<td>Backgrd RATE : 0.321712</td>
<td>0.0770759</td>
</tr>
<tr>
<td>(BG/min): +/- 0.0193999</td>
<td>+/- 0.00851161</td>
</tr>
<tr>
<td>Peak significance is 1.6156 deg from Source location.</td>
<td></td>
</tr>
</tbody>
</table>

#### Wobble Analysis Result for VEGAS version: heads/v2_5_7

Total On events : 32 Total Off events : 203
Total Exposure Time: 97.43859 Alpha : 0.1481481 (from rel exposure)
There are mixed alphas : 0.1428571 0.1666667
Significance : 0.3239028
Rate_Gamma = 0.01976554 +/- 0.06196551
Rate_Bg = 0.3088637
Rate_Bg / Rate_Gamma^2 = 790.5869

### ITM Analysis

<table>
<thead>
<tr>
<th>Source Location</th>
<th>Max Sig Location</th>
</tr>
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<tr>
<td>RA (deg) : 330.078</td>
<td>329.461</td>
</tr>
<tr>
<td>Dec (deg) : 26.9158</td>
<td>25.3982</td>
</tr>
<tr>
<td>ON counts : 12</td>
<td>26</td>
</tr>
<tr>
<td>OFF counts : 288</td>
<td>267</td>
</tr>
<tr>
<td>EXCESS counts : 1.40564</td>
<td>16.1581</td>
</tr>
<tr>
<td>Alpha param. : 0.036786</td>
<td>0.036861</td>
</tr>
<tr>
<td>Alpha unc. : 0.00548855</td>
<td>0.00551456</td>
</tr>
<tr>
<td>SIGNIFICANCE : 0.373542</td>
<td>3.69326 (34m sigma)</td>
</tr>
<tr>
<td>EXPOSURE (min): 97.4386</td>
<td></td>
</tr>
<tr>
<td>Integral acc. : 0.030934</td>
<td>0.0307723</td>
</tr>
<tr>
<td>RATE (gam/min): 0.0144259</td>
<td>0.165829</td>
</tr>
<tr>
<td>: +/- 0.0361243</td>
<td>+/- 0.0526944</td>
</tr>
<tr>
<td>Backgrd RATE : 0.108729</td>
<td>0.101006</td>
</tr>
<tr>
<td>(BG/min): +/- 0.00640689</td>
<td>+/- 0.00618146</td>
</tr>
<tr>
<td>Peak significance is 0.1909 deg from Source location.</td>
<td></td>
</tr>
</tbody>
</table>

#### Wobble Analysis Result for VEGAS version: heads/v2_5_7

Total On events : 12 Total Off events : 114
Total Exposure Time: 97.43859 Alpha : 0.09090909 (from rel exposure)
Significance : 0.4736231
Rate_Gamma = 0.01679379 +/- 0.03692089
Rate_Bg = 0.1063607
Rate_Bg / Rate_Gamma^2 = 377.1234
GRB150423A

Standard Analysis

ITM Analysis

Miles Garcia
Nevis Labs REU 2021 Final Presentation
**Source Location | Max Sig Location**

**GRB150423A**

<table>
<thead>
<tr>
<th>Source Location</th>
<th>Max Sig Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (deg) : 221.579</td>
<td>220.537</td>
</tr>
<tr>
<td>Dec (deg) : 12.283</td>
<td>13.9267</td>
</tr>
<tr>
<td>ON counts : 252</td>
<td>76</td>
</tr>
<tr>
<td>OFF counts : 2108</td>
<td>494</td>
</tr>
<tr>
<td>EXCESS counts : 9.61952</td>
<td>29.521</td>
</tr>
<tr>
<td>Alpha param. : 0.114981</td>
<td>0.0940869</td>
</tr>
<tr>
<td>SIGNIFICANCE : 0.580953</td>
<td>3.75734</td>
</tr>
<tr>
<td>EXPOSURE (min): 122.218</td>
<td></td>
</tr>
<tr>
<td>Integral acc. : 0.0935608</td>
<td>0.0150432</td>
</tr>
<tr>
<td>RATE (gam/min): 0.0787081</td>
<td>0.241545</td>
</tr>
<tr>
<td>: +/- 0.136881</td>
<td>+/- 0.0733536</td>
</tr>
<tr>
<td>Backgrd RATE : 1.98319</td>
<td>0.380296</td>
</tr>
<tr>
<td>(BG/min): +/- 0.0431945</td>
<td>+/- 0.0171103</td>
</tr>
<tr>
<td>Peak significance is 1.9319 deg from Source location.</td>
<td></td>
</tr>
</tbody>
</table>

**Wobble Analysis Result for VEGAS version: heads/v2_5_7**

Total On events : 231 Total Off events : 1623
Total Exposure Time: 122.2176 Alpha : 0.1428571 (from rel exposure)
Significance : -0.05269245
Rate_Gamma = -0.007013251 +/- 0.1329746
Rate_Bg = 1.897084

**ITM Analysis**

<table>
<thead>
<tr>
<th>Source Location</th>
<th>Max Sig Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (deg) : 221.579</td>
<td>220.345</td>
</tr>
<tr>
<td>Dec (deg) : 12.283</td>
<td>13.3226</td>
</tr>
<tr>
<td>ON counts : 89</td>
<td>51</td>
</tr>
<tr>
<td>OFF counts : 2047</td>
<td>667</td>
</tr>
<tr>
<td>EXCESS counts : 7.68901</td>
<td>24.9581</td>
</tr>
<tr>
<td>Alpha param. : 0.039722</td>
<td>0.0390433</td>
</tr>
<tr>
<td>SIGNIFICANCE : 0.741004</td>
<td>4.00493</td>
</tr>
<tr>
<td>EXPOSURE (min): 122.218</td>
<td></td>
</tr>
<tr>
<td>Integral acc. : 0.0314742</td>
<td>0.00959696</td>
</tr>
<tr>
<td>RATE (gam/min): 0.0629124</td>
<td>0.20421</td>
</tr>
<tr>
<td>: +/- 0.0785782</td>
<td>+/- 0.0590117</td>
</tr>
<tr>
<td>Backgrd RATE : 0.665297</td>
<td>0.213078</td>
</tr>
<tr>
<td>(BG/min): +/- 0.0147047</td>
<td>+/- 0.00825042</td>
</tr>
<tr>
<td>Peak significance is 1.5902 deg from Source location.</td>
<td></td>
</tr>
</tbody>
</table>

**Wobble Analysis Result for VEGAS version: heads/v2_5_7**

Total On events : 87 Total Off events : 862
Total Exposure Time: 122.2176 Alpha : 0.09090909 (from rel exposure)
Significance : 0.9162808
Rate_Gamma = 0.07066382 +/- 0.07938095
Rate_Bg = 0.6411812
Rate_Bg / Rate_Gamma^2 = 128.4064
Source Location | Max Sig Location
--- | ---
[34m++] RA (deg): 10.319 | 11.4172
[34m++] Dec (deg): 33.995 | 33.7202
[34m++] ON counts: 106 | 130
[34m++] OFF counts: 989 | 621
[34m++] EXCESS counts: -20.7007 | 38.8176
[34m++] Alpha param.: 0.12811 | 0.146832
[34m++] SIGNIFICANCE: -1.7879 | 3.53572 [34m sigma
[34m++] EXPOSURE (min): 111.092
[34m++] Integral acc.: 0.0916076 | 0.0732302
[34m++] RATE (gam/min): -0.186338 | 0.349417
[34m++] : +/- 0.0995195 | +/- 0.107789
[34m++] Backgrd RATE: 1.1405 | 0.820782
[34m++] (BG/min): +/- 0.0362658 | +/- 0.0329368
[34m++]
[34m++] Peak significance is 0.9524 deg from Source location.

Wobble Analysis Result for VEGAS version: heads/v2_5_7
Total On events: 107 Total Off events: 684
Total Exposure Time: 111.0922 Alpha: 0.1724138 (from rel exposure)
There are mixed alphas: 0.1666667 0.25 0.1428571
Significance: -0.9467619
Rate_Gamma = -0.09839604 +/- 0.101575
Rate_Bg = 1.075576
Interpreting the Results & Next Steps

- Note: 2 GRBs did not make it through VEGAS Analysis... errors
- Of the remaining 4 GRBs:
  - No detections-- highest significance = 1.10 for GRB201216C
  - Can still shoot for upper limit calculations
- Goal: Could VERITAS detect these GRBs in an ideal world (if we observed them at the right time, with right conditions, etc)?

Light curve for GRB180720B (first VHE GRB detection by HESS) with HESS UL

https://doi.org/10.1038/s41586-019-1743-9
Calculating Flux Upper Limits

VEGAS UL Results Give Us:

- Form of the differential photon flux \( \frac{dN}{dE} \) and index:
  \[
  \frac{dN}{dE} = k_0 \left( \frac{E}{E_0} \right)^{-2.5}
  \]

- Integral photon flux:
  \[
  \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN}{dE} \, dE
  \]

- Energy range, \( E_{\text{min}} \) and \( E_{\text{max}} \), used to calculate integral photon flux

We want to find:

- Value of the normalization factor \( k_0 \)

- Integral Energy Flux:
  \[
  \int_{E_{\text{min}}}^{\infty} \frac{dN}{dE} E \, dE \]

  Upper Limit when integrating to infinity.

  Also need to convert to erg cm\(^{-2}\) s\(^{-1}\) for Flux UL.

\( E_0 = 1 \text{ TeV} \) in our case...
Flux UL Results

- Although Luminosity upper limits were originally calculated, the light curves for these GRBs were in Flux units, so the luminosity upper limits were converted back to flux, in units of erg cm$^{-2}$ s$^{-1}$.

<table>
<thead>
<tr>
<th>GRB</th>
<th>Flux UL (standard) (erg cm$^{-2}$ s$^{-1}$)</th>
<th>Luminosity UL (standard) (erg/s)</th>
<th>Flux UL (itm) (erg cm$^{-2}$ s$^{-1}$)</th>
<th>Luminosity UL (itm) (erg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150120A</td>
<td>4.15e-12</td>
<td>3.16e+45</td>
<td>5.45e-12</td>
<td>4.17e+45</td>
</tr>
<tr>
<td>150423A</td>
<td>4.10e-12</td>
<td>3.16e+45</td>
<td>3.62e-12</td>
<td>2.79e+45</td>
</tr>
<tr>
<td>170428A</td>
<td>1.06e-11</td>
<td>8.34e+45</td>
<td>7.03e-12</td>
<td>5.53e+45</td>
</tr>
<tr>
<td>201216C</td>
<td>1.13e-11</td>
<td>7.50e+46</td>
<td>5.88e-12</td>
<td>3.89e+46</td>
</tr>
</tbody>
</table>
Flux UL Final Steps: Plotting on Light Curves

- Light Curve: Flux over time
- Flux measured by other telescopes (SWIFT-XRT)
- We can plot our UL value on the light curve and see how it matches with observed flux values
- If Flux UL < Observed Flux, we could have observed the GRB at that time (ideally)
Light Curve Plots + Interpretation

Green = Standard Analysis
Red = ITM Analysis
Outline

Introduction
- Gamma Rays
- Sources of Gamma Rays & GRBs
- IACTs & VERITAS

GRB Analysis
- Selecting GRBs for Analysis
- VEGAS Analysis Process
- VEGAS Results
- Calculating Upper Limits

VEGAS Testing
- Process
- Results

Conclusions and The Future
Motivation & Process

Motivation:

- When doing the GRB Analysis, we encountered some errors in the newest version of VEGAS (ITM+v2.5.8)
- Reverted to older version of the package to do the analysis
- Want to know: What pathways are currently functioning? Which are not-- and why (what errors?)

Process:

- 3 settings: v2.5.7, v2.5.8; ITM Analysis on/off; TDRBM analysis on/off
- 8 total configurations to test
- Used a small Crab dataset-- standard candle

http://www.nasa.gov/sites/default/files/thumbnails/image/crab-nebula-mosaic.jpg
## VEGAS Testing Results

<table>
<thead>
<tr>
<th>Version</th>
<th>Standard Analysis</th>
<th>ITM Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>v 2.5.7</td>
<td>Success</td>
<td>Success</td>
</tr>
<tr>
<td>TDRBM Off</td>
<td>Noncritical TS error (completed)</td>
<td>Noncritical TS error (completed)</td>
</tr>
<tr>
<td>v 2.5.8</td>
<td>Success</td>
<td>Stage 4 Segfault (failed)</td>
</tr>
<tr>
<td>TDRBM On</td>
<td>Stage 6 EA Check / Runlist error (failed)</td>
<td>Stage 4 Segfault (failed)</td>
</tr>
</tbody>
</table>
Outline

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Conclusions and The Future
Conclusions

**GRB Analysis**
- No detections from the 4 GRBs that were successfully analyzed
- Upper Limits suggest VERITAS still has the capacity to detect some of these GRBs, just need to catch them at the right time (not easy!)

**VEGAS Testing**
- 3 successful configs, 2 finished with errors, 3 failed
- Issues recorded, saved log and error files.
- Hopefully issues can get resolved
The Future

- EBL Correction for UL-- more accurate understanding of UL results
- Re-do analysis with better VEGAS configuration (2.5.8+ITM+TDRBM)(when it works)
- Soon: CTA!! Better sensitivity, better energy range, faster slewing = better results

https://www.cta-observatory.org/
Thank you!

Thanks to Professors Reshmi Mukherjee and Brian Humensky, to Deivid Ribeiro, Colin Adams, Massimo Capasso, and Qi Feng, and to the other REU and SRI students, as well as the rest of the VERITAS team for their guidance, help, and motivation over the summer.

Special thanks to the NSF for funding the REU program, and to Georgia Karagiorgi, John Parsons, and Amy Garwood for running the program.
Mukherjee, R., for the VERITAS Collaboration. “Observing the energetic universe at very high energies with the VERITAS gamma ray observatory.” Advances in Space Research 62 (2018): 2828-2844.


Gammapy EBL absorption: https://docs.gammapy.org/dev/modeling/gallery/spectral/plot_absorbed.html

VERITAS info: https://veritas.sao.arizona.edu/about-veritas

### Full GRB Weight Calculation Info

#### Selected VERITAS GRBs

<table>
<thead>
<tr>
<th>GRB</th>
<th>Ra (deg)</th>
<th>Dec (deg)</th>
<th>$z$</th>
<th>Zenith Angle (deg)</th>
<th>Energy Threshold (GeV)</th>
<th>Observing Delay (s)</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>150120A</td>
<td>10.319</td>
<td>33.995</td>
<td>0.460</td>
<td>40</td>
<td>250</td>
<td>370</td>
<td>8.17E-04</td>
</tr>
<tr>
<td>150423A</td>
<td>221.579</td>
<td>12.283</td>
<td>0.456</td>
<td>27</td>
<td>150</td>
<td>83</td>
<td>7.86E-03</td>
</tr>
<tr>
<td>160509A</td>
<td>311.75388</td>
<td>76.10811</td>
<td>1.17</td>
<td>50</td>
<td>450</td>
<td>1977</td>
<td>3.01E-08</td>
</tr>
<tr>
<td>170428A</td>
<td>330.07823</td>
<td>26.91584</td>
<td>0.454</td>
<td>60</td>
<td>650</td>
<td>1458</td>
<td>6.63E-06</td>
</tr>
<tr>
<td>170519A</td>
<td>163.42688</td>
<td>25.37431</td>
<td>0.818</td>
<td>57.4</td>
<td>610</td>
<td>116</td>
<td>1.80E-06</td>
</tr>
<tr>
<td>201216C</td>
<td>16.37032</td>
<td>16.51612</td>
<td>1.10</td>
<td>22</td>
<td>130</td>
<td>8850</td>
<td>2.77E-05</td>
</tr>
</tbody>
</table>

#### Tevcat GRBs

<table>
<thead>
<tr>
<th>GRB</th>
<th>Ra (deg)</th>
<th>Dec (deg)</th>
<th>$z$</th>
<th>Energy Threshold (GeV)</th>
<th>Observing Delay (s)</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>180720B</td>
<td>0.767</td>
<td>-2.830</td>
<td>0.654</td>
<td>n/a</td>
<td>100</td>
<td>57</td>
</tr>
<tr>
<td>190114C</td>
<td>54.71</td>
<td>-26.877</td>
<td>0.4245</td>
<td>n/a</td>
<td>300</td>
<td>36000</td>
</tr>
<tr>
<td>190829A</td>
<td>44.5417</td>
<td>-8.9578</td>
<td>0.0785</td>
<td>n/a</td>
<td>200</td>
<td>15600</td>
</tr>
<tr>
<td>201216C</td>
<td>16.37032</td>
<td>16.51612</td>
<td>1.10</td>
<td>n/a</td>
<td>300*</td>
<td>57</td>
</tr>
</tbody>
</table>

*GRB201216C Energy Threshold uncertain for MAGIC detection (Tevcat)
- Get rid of parts of a run where there were weather/hardware issues, or if the telescopes weren’t pointing at the source yet.

### Time Cuts

<table>
<thead>
<tr>
<th>GRB</th>
<th>Time Cuts (Run</th>
<th>cut start/cut finish)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150120A</td>
<td>76034</td>
<td>480/523</td>
</tr>
<tr>
<td>150423A</td>
<td>77423</td>
<td>0/2400</td>
</tr>
<tr>
<td></td>
<td>77424</td>
<td>1200/1590</td>
</tr>
<tr>
<td>160509A</td>
<td>82007</td>
<td>1440/1800</td>
</tr>
<tr>
<td>170428A</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>170519A</td>
<td>86207</td>
<td>0/192</td>
</tr>
<tr>
<td></td>
<td>86210</td>
<td>1620/1801</td>
</tr>
<tr>
<td></td>
<td>86211</td>
<td>600/690</td>
</tr>
<tr>
<td>201216C</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>
VEGAS UL Results for GRBs

<table>
<thead>
<tr>
<th>GRB</th>
<th>Energy Threshold (standard) (TeV)</th>
<th>Integral UL (standard) (TeV^{-1}s^{-1}m^{-2})</th>
<th>Energy Threshold (itm) (TeV)</th>
<th>Integral UL (itm) (TeV^{-1}s^{-1}m^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>150120A</td>
<td>0.288</td>
<td>3.02e-8</td>
<td>0.288</td>
<td>3.98e-8</td>
</tr>
<tr>
<td>150423A</td>
<td>0.138</td>
<td>6.22e-8</td>
<td>0.166</td>
<td>4.57e-8</td>
</tr>
<tr>
<td>170428A</td>
<td>0.457</td>
<td>4.87e-8</td>
<td>0.38</td>
<td>3.88e-8</td>
</tr>
<tr>
<td>201216C</td>
<td>0.138</td>
<td>1.72e-7</td>
<td>0.166</td>
<td>7.42e-8</td>
</tr>
</tbody>
</table>

* $E_{\text{max}} = 30$ TeV for all GRBs

- Then used python code to get Flux UL and do unit conversions
- Flux to luminosity-- need distance, from redshift
  - Depends slightly on the cosmology model you choose.
Why Study Gamma Rays-- Further Uses!

- **Dark Matter Searches**

- **Intergalactic Magnetic Field Constraints**

- **Testing Lorentz Invariance**

\[ G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]