The Low Energy Array of A Major Future VHE Gamma-ray Experiment

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Major Physics Goals

- Further observation of SNR: Origin of Cosmic Rays
- Detailed studies of physics of AGN jets
- Cosmology link: EBL $\gamma$-ray absorption
- Resolving morphology and spectra of $\gamma$-rays from PWN
- Detection of pulsed $\gamma$-ray emission from Pulsars
- Search for Dark Matter
- Observation of $\gamma$-ray Bursts
- etc

Extent of energy spectra below 100 GeV is highly desirable!
## Major Imaging Cherenkov Telescopes

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Height</th>
<th>Current status</th>
<th>Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANGAROO</td>
<td>Australia, Woomera</td>
<td>-31.1</td>
<td>221.2 W</td>
<td>160 m</td>
<td>4 x 10 m</td>
<td></td>
</tr>
<tr>
<td>HESS</td>
<td>Namibia</td>
<td>-23.3</td>
<td>16.5 W</td>
<td>1800 m</td>
<td>4 x 12 m</td>
<td>+ 28 m in 2008</td>
</tr>
<tr>
<td>HESS-II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAGIC</td>
<td>Canary Island La Palma</td>
<td>28.7</td>
<td>17.9 W</td>
<td>2200 m</td>
<td>17 m</td>
<td>+ 17 m in 2007</td>
</tr>
<tr>
<td>MAGIC-II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High Q.E.</td>
</tr>
<tr>
<td>VERITAS</td>
<td>Arizona, USA</td>
<td>32</td>
<td>111.6 W</td>
<td>1275 m</td>
<td>4 x 12 m</td>
<td></td>
</tr>
<tr>
<td>MACE</td>
<td>India, Hanle</td>
<td>32.7</td>
<td>281.0 W</td>
<td>4200 m</td>
<td></td>
<td>21 m in 2010</td>
</tr>
</tbody>
</table>
Problems at low energies

- **Muons** can be rejected by stereo trigger
- **Electrons** contribute to background
- **Geomagnetic effect** deteriorates images
- **Hadron** rejection is poor
- **Angular resolution** becomes critical

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Low Photon Statistics at Low Energies

- Poor photon statistics, e.g. for a 17 m CT
  - 30 GeV ~700 photons/telescope → ~ 80 ph.e.
  - 10 GeV ~250 photons/telescope → ~ 30 ph.e.
    It does not trigger the telescope!

- Sampling factor* for a 17 m CT
  - mirror/light pool ~1/100
  - photon → ph.e. ~1/10
  - total efficiency ~1/1000

*ratio of detected photons to generated ones
Enhance Photon Statistics

- **Large telescope:**
  - HESS-II (28 m), ECO-1000 (34 m)

- **High Q.E. photon detectors:**
  - HPD, SiPM developments for MAGIC-II

- **High Altitude:**
  - MACE (4.2 km)
Sensitivity Gain at Low Energies

Major parameter: photon statistics

HESS/VERITAS: $4 \times 100 \text{ m}^2 \times 0.1 = 40 \text{ m}^2$ (eff. area)
sampling factor $\sim 10^{-3}$

Next step: to achieve sampling factor $\sim 10^{-2}$

Possible scenario:
- reasonable site $\sim 3 \text{ km altitude} \times 1.3$
- effective mirror area $\sim 120 \text{ m}^2 \times 3$
- advanced photo detectors $\times 2.5$

(leave it for future upgrades!)

Overall factor: $\times 4 \ (\times 10)$

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Various Alternatives

Telescope costs: \( \sim (D/12)^{2.7} \) M$  
Camera costs: \( \sim 1 \) M$ (500$ per channel x 2000 channels)  
Total costs: \( \text{No. of tel.-s.} \times [(D/12)^{2.7} + 1] \) M$  
Energy threshold: \( \sim 100 \text{ GeV} \times (12/D)^{1/2} \)

<table>
<thead>
<tr>
<th>D, m</th>
<th>( A_{\text{eff}}, \text{ m}^2 )</th>
<th>No. of tel-s.</th>
<th>Tel. costs</th>
<th>Total costs</th>
<th>( E_{\text{th}}, \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>11.2</td>
<td>11</td>
<td>1</td>
<td>11</td>
<td>100</td>
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<tr>
<td>14</td>
<td>15.4</td>
<td>8</td>
<td>1.5</td>
<td>12</td>
<td>73</td>
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<td>17</td>
<td>22.6</td>
<td>6</td>
<td>2.5</td>
<td>15</td>
<td>50</td>
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<tr>
<td>20</td>
<td>31.4</td>
<td>4</td>
<td>4.0</td>
<td>16</td>
<td>36</td>
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<tr>
<td>24</td>
<td>45.2</td>
<td>3</td>
<td>6.5</td>
<td>19.5</td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>70.6</td>
<td>2</td>
<td>12.</td>
<td>24</td>
<td>16</td>
</tr>
</tbody>
</table>
Energy Threshold vs Costs

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Low Energy Stereo Array

We know:
Minimum number of telescopes is 3!

We don’t know:
- Which aperture?
- Baseline distance

Large scale array can be composed of triplets
Design Studies

System layout

3 telescopes (parabolic dish)
Baseline distance: 50, 80, 100 m
Telescope size: 12, 17, 20, 24, 30 m
Camera: various configurations

Monte Carlo simulations

Energy range: 10 GeV - 1 TeV
Impact distance: 0 - 10^3 m
Primaries: \( \gamma \) rays, protons
Stereo Event

17 m $\varnothing$

T2

T3

Combined Camera View

Center (-67.93m, 21.67m), E = 103.519 GeV
Stereo Event

20 m \( \varnothing \)

T2

T3

Combined Camera View

Center (-67.93m, 21.67m), E = 103.519 GeV
Stereo Event

24 m $\varnothing$

Combined Camera View

Center (-67.93m, 21.67m), E = 103.519 GeV
Stereo Event

30 m Ø

T2

T1

T3

Combined Camera View

Center (-67.93m, 21.67m), E = 103.519GeV
Baseline Distance

Large separations substantially suppress 3 telescope events!
Go for close-packed stereo array!

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Detection Areas & Rates

\[ \gamma \text{ rays, 2 out 3 tel. trigger, 50 m separation} \]

**Collection areas**

**Detection rates**

Energy threshold is well below 100 GeV!

Limit by FoV!

Low energy threshold!
Integral Detection Rates

Array of 30 m telescopes
Raw event rate : 1.3 kHz
γ-ray rate : 4.5 Hz

Still maintainable rate without online topological trigger!
Angular Resolution

Angular resolution improves with aperture!

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Single Telescope Analysis

‘Straightforward’ approach:

- Simultaneously ‘orientation’ & ‘shape’
- Standard image parameters
- Non-parametric estimation of multivariate probability density
- Bayesian decision rules
- Test on MC simulated events

In the energy range of 10-30 GeV the maximum achievable Q-factor is about 3.0 for the 50% γ-ray acceptance.

Konopko, Chilingarian, Reimers (2006)
Time-Dependent Analysis

- ‘Centroid’ is close to the center of FoV
- Small angular size
- Very high fluctuations of image shape

C-light image of a 10 GeV γ-ray shower averaged over a sample of events.

7.25-7.5 ns
8.25-8.5 ns
9.5-9.5 ns
10-12 ns
Reflector

- A 20-26 m dish-mount is technically easy!
- Focal length of 25-35 m
- Parabolic dish is preferable
  - Small time spread of reflected light
  - Good PSF for off-axis light (<2.0°)
- Glass mirrors are ok
- Automatic mirror adjustment
- Camera auto focus [dislocation by ~20 cm]
- High slewing speed: 200 deg/min
- Approximate cost: $4-8M
Optical Quality

Ray-tracing simulations
Davies-Cotton design

$\sigma = 0.142^\circ$

$\sigma = 0.114^\circ$

$\sigma = 0.088^\circ$

$D = 20\text{ m f/1}$

$90\%$ Encircled Fraction ($^\circ$)

$R$ ($^\circ$)
Camera

- **FoV of ~4°-5° diameter**
  - Limited by a broad PSF at large off-set
  - Low energy events shrink to the camera center
  - Scan window of about 2° diameter
- **Small pixels of ~0.09°**
  - Reduce n.s.b. contamination
  - Better imaging of low energy events
  - Limited by PSF for a 20 m dish
- **Homogeneous design**
- **Custom PMs**
- **Fast electronics**
- **Approximate cost: ~$1-1.5M**
Sensitivity vs Costs

S/N* : signal-to-noise ratio
Crab-like source
(not optimized)

Total costs: 3 large IACTs

*given in arbitrary units

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Sensitivity vs Costs

Array of 3 IACTs: 20-25m Ø
Total costs: ~15-28.5 M$

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Sensitivity

Integral flux sensitivity for $dN/dE \propto E^{-2.8}$ point-like source, $\theta = 0$ to $30^\circ$

GLAST (1 year)

50 hours, $5 \sigma$

Minimum integral flux, $\Phi_{\gamma E}$ (cm$^{-2}$ s$^{-1}$)

$F_{\gamma}^{\text{min}} (> 20\text{GeV}) \propto 6 \cdot 10^{-11} (D / 17m)^{-2.5} \text{cm}^{-2} \text{s}^{-1}$

3 x 20 m CT

Lower Energy Threshold

Gain at 100 GeV

HESS II

1% Crab Flux
Conclusions

- Reduction of energy threshold is likely to remain a significant drive for VHE $\gamma$-ray astronomy
- Next generation of ground-based imaging atmospheric Cherenkov detectors need a low energy array
- 3 telescopes of 20-26 m diameter is a good start!
- Such a detector will help to achieve many scientific goals as currently perceived by $\gamma$-ray astrophysics community!
Low Energy Events

Longitudinal development, C-light emission of a 10 GeV γ-ray shower.

Average time pulses of the C-light emission from a 10 GeV γ-ray shower.

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