Towards Gamma-ray astronomy with timing-arrays

Martin Tluczykont
ECRS 2014, Kiel
Gamma-ray astronomy
Gamma-ray astronomy
Measuring cosmic-ray and gamma-ray air showers

First interaction (usually several 10 km high)

Air shower evolves (particles are created and most of them later stop or decay)

Measurement of Cherenkov light with telescopes

Some of the particles reach the ground

Measurement with scintillation counters

Radio

Measurement of particles with tracking detectors (with drift chambers or streamer or Geiger tubes)

Measurement of low-energy muons with scintillation or tracking detectors

ICECUBE

Measurement of high-energy muons deep underground

Source: A. Karle 2006
## Timing arrays and detection methods for gamma astronomy

<table>
<thead>
<tr>
<th>Method</th>
<th>$E_{\text{thr}}$</th>
<th>Angular resolution</th>
<th>$\Delta E/E$</th>
<th>$\gamma/h$</th>
<th>Duty cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>$\sim 3$ TeV</td>
<td>$\sim 1^\circ$</td>
<td>30-50%</td>
<td>$\sim 1$</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Water: 100 GeV</td>
<td>$&lt;0.5^\circ$</td>
<td></td>
<td>$\sim 6$</td>
<td></td>
</tr>
<tr>
<td>Cherenkov</td>
<td>IACTs: 5 GeV</td>
<td>0.1-0.2$^\circ$</td>
<td>10-15%</td>
<td>$\sim 4$</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>NonI: 10 TeV</td>
<td></td>
<td></td>
<td>$\sim 1.5-2$</td>
<td></td>
</tr>
<tr>
<td>fluoresc.</td>
<td>$10^{17}$ eV</td>
<td>$&gt;1^\circ$</td>
<td>10-15%</td>
<td>?</td>
<td>10%</td>
</tr>
<tr>
<td>Radio</td>
<td>$10^{17}$ eV</td>
<td>$&gt;1^\circ$</td>
<td>10-15%</td>
<td>?</td>
<td>100%</td>
</tr>
</tbody>
</table>
$	extbf{Cherenkov:}$

"Integrating calorimeter"
Timing of air showers

Arrival time distribution in one bin

$\sigma \times C = \text{thickness}$

J.D. Haverhoek 2006

particle 1

particle 2

direction of primary

wave-front

bin

ground
Timing of air showers

- Particle front disk width: ~30ns @ 100 m
- Cherenkov light front: disk width: <10 ns @ 100 m
Air Cherenkov imaging and timing

H.E.S.S. Telescopes

Past: Themistocle, AIROBICC
Today: HiSCORE, TAIGA

MAGIC camera image
# Air Cherenkov imaging and timing

<table>
<thead>
<tr>
<th></th>
<th>Imaging ACTs</th>
<th>Timing arrays</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direction</strong></td>
<td>Image orientation</td>
<td>Shower front arrival times</td>
</tr>
<tr>
<td><strong>Particle type</strong></td>
<td>Image shape</td>
<td>Lateral density function</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arrival times</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time width (FWHM)</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>Ch. photon count</td>
<td>Ch. photon count</td>
</tr>
</tbody>
</table>
Upcoming timing arrays: HiSCORE and TAIGA
Tunka-HiSCORE

- Tunka-133: 1 km² dense array
- Energy threshold $10^{15}$ eV
- Tunka-HiSCORE: 9-station array … 25+stations
Tunka-HiSCORE Status

Prototype-array:

- 9 stations, 300m X 300m
- 150m inter-station distance
- 2 parallel DAQ systems
- Energy threshold: <30 TeV

Future:

- Projected $E_{\text{thr}}$: 10 TeV
  graded array and clipping

Station:

- 0.5 m² light collection
- 4 channels (PMT + Cone)
Tunka-HiSCORE Status

Prototype-array:

- 9 stations, 300m X 300m
- 150m inter-station distance
- 2 parallel DAQ systems
- Energy threshold: <30 TeV

Future:

- Projected $E_{\text{thr}}$: 10 TeV
- graded array and clipping

Also see:
Kozhin, V. “A DAQ System for Tunka-HiSCORE”, S8-234
Epimakhov, S. “Amplitude calibration for Tunka-HiSCORE”, S4-425
Reconstruction

Tunka-133 [Berezhnev et al. 2012NIMPA.692...98B]
HiSCORE [Hampf et al. 2013NIMPA.712..137H]

HiSCORE event display
500 TeV gamma-ray Simulation

Intensity [p.e.] 0 - 1912
Peaktime [ns] -446 - 526
Reconstruction

- Shower core position 1 (cog)
- Preliminary direction (time plane fit)
- Improved core position: light distribution function (LDF) fitting
- Improved direction: arrival time model
- Fit of signal time widths
Arrival time model

2013NIMPA.712..137H

dt(k, z) = \frac{1}{c} \left( \sqrt{k} - \frac{z}{\cos(\theta)} + \frac{8.0}{z} \sqrt{k} \eta_0 \left( 1 - \exp \left( \frac{-z}{8.0} \right) \right) \right)

k(r, z) = r^2 + z^2 \frac{1}{\cos(\theta)^2} + 2rz \tan(\theta) \cos(\delta)

\delta = \phi + \text{atan2}((x_{Det} - x_{core}), (y_{Det} - y_{core}))
Arrival time model

\[ dt(k, z) = \frac{1}{c} \left( \sqrt{k} - \frac{z}{\cos(\theta)} + \frac{8.0}{z} \sqrt{\kappa \eta_0} \left( 1 - \exp \left( \frac{-z}{8.0} \right) \right) \right) \]

\[ k(r, z) = r^2 + z^2 \frac{1}{\cos(\theta)^2} + 2 rz \tan(\theta) \cos(\delta) \]

\[ \delta = \phi + \text{atan2} \left( (x_{Det} - x_{core}), (y_{Det} - y_{core}) \right) \]
Angular resolution

Crucial: relative time-synchronization <1ns

Two time-calibration systems:
DRS4 sampling of 100 MHz frequency
WhiteRabbit system
Time calibration

Time Resolution < 0.6 ns!
Energy determination

Energy → light density

\[ Q(x) = \text{LDF at } x \text{ m} \]
Energy determination

HiSCORE simulation

![Graph showing energy resolution vs. energy for different particle species.](image)
Particle separation X_{max} vs. E

![Graph showing X_{max} vs. MC Energy for different particle types: Gamma-rays, Protons, Iron nuclei]
Shower maximum

- **Time model method**: $X_{\text{max}}$ free parameter in arrival time model
- **LDF method**: $X_{\text{max}}$ from LDF slope, $Q_{50}/Q_{220}$
- **Width method**: $X_{\text{max}}$ from signal width

![Graph showing relationship between signal width and core distance](image)

- $X_{\text{max}} = 495 \text{ g/cm}^2$
- $X_{\text{max}} = 718 \text{ g/cm}^2$

![Graph showing relationship between $X_\theta/\cos\theta$ and $X_{\text{max}}$, and log scale for FWHM](image)

Prosin, ECRS 2010

D. Hampf, MT, D. Horns, NIMA 2013
Shower maximum

HiSCORE Simulation

![Graph showing the depth resolution vs energy for different showers and simulations. The graph includes data for Timing, LDF, widths, and combined conditions.]
Particle separation timing

Systematic difference
Cherenkov signal
rise times
Particle separation Q-factor

- $X_{\text{max}}$ vs. $E$
- Shower front rise time
- Systematic differences between $X_{\text{max}}$ reconstruction methods

![Graph showing survival probabilities and QF versus energy in TeV]
Sensitivity
Tunka-HiSCORE → TAIGA
Tunka Advanced Instrument for Gamma ray and cosmic ray physics

10/2014: extension
- Additional 25 stations
- First telescope
- Tilting mode

2015+:
- 10 telescopes
- Hybrid timing+imaging
- Muon detectors
TAIGA Telescopes

- Dish: Davies-cotton tesselated, 34 mirrors (60cm)
- 4.3 m dish diameter
- 4.75 m focal length
- F/D ~ 1.2
- 397 PMT camera foV 8° (0.38° / pixel)
- Proven design components
Non-imaging and imaging hybrid detection
Telescope image scaling

Central reconstruction parameter: **Shower core position** $D_K$

\[
\begin{align*}
    w_{MC} &= w_{MC}(\text{size}, D_K, \vartheta) \\
    mscw &= \frac{1}{N_{Tel}} \sum_{k=1}^{N_{Tel}} \frac{\text{width}}{w_{MC}}
\end{align*}
\]
Hybrid imaging + non-imaging

~100 m

Imaging (stereo)

600 m
Hybrid Image scaling:

\[ D_K \text{ from timing array} \]

Image from telescope(s)

\[ \rightarrow \text{large inter-telescope distance} = \text{large } A_{\text{eff}} \]

\[ \rightarrow \text{scaled width separation parameter} \]

(+ stereo at high energies, mean scaled width)
HiSCORE + IACTs

Preliminary results hybrid width scaling:

- Improves gamma-hadron separation
- Increases total area as compared to stereoscopic array

Also see:
Kunnas, M.
“Simulation of TAIGA”

Apply scaled width cut:

Q-factor ~2.2
(Simulated granularity: 0.5°)
Hybrid events: Sensitivity

![Graph showing sensitivity analysis with different datasets and energy levels.]

- CTA survey
- LHAASO point-source, 1 year
- IceCube Milagro sources, 5 years (v)
- KASCADE U.L.
- H.E.S.S. survey, hard sources
- MGRO J1908+06
- HESS J1908+06

September 3, 2014
martin.tluczykont@physik.uni-hamburg.de
Astronomy

Accessing a new energy range (E>10TeV)

- Pevatrons
- Diffuse Galactic emission
- Absorption by pair production with Interstellar photon field
  - Indirect measurement of field density
  - Distance measurement using gamma-ray spectra
- Heavy dark matter
- Unexpected discoveries...
Summary

- **Timing information**
  - Best provided by air Cherenkov technique
  - Complementary to imaging
  - Combination with imaging promising

- **Large arrays possible with low level of complexity**

- **Potential for opening up gamma-ray astronomy in the multi-TeV regime**
Backup slides
Time calibration

\[ h_{\text{stationPlaneResiduals}_2}\_\text{st2} \]
- Entries: 5537
- Mean: -0.05835
- RMS: 0.4902

\[ h_{\text{rec th}_Vic} \]
- Entries: 747
- Mean: 15.5
- RMS: 8.603
- Underflow: 0
- Overflow: 0

Shower front

HiSCORE detector stations
Sky coverage

**Standard observation mode:** station points to zenith

**Tilted mode:** inclined along the north-south axis.

Tilting: coverage of different parts of the sky.

Tilted south mode: 110 h on the Crab Nebula, after weather corrections.
Past experiments

- Themistocle
- AIROBICC
### AIROBICC results

![Graph showing Intensity vs. Energy for Crab Nebula](image)

| Nr. | Objekt   | \( N_{QB} \) \( = \alpha \cdot N_{BG} \) | \( \hat{N}_{QB} \) | \( N_{OG} \) | \( S_{DC} \) \( [\sigma] \) | \( S_{\text{burst, exp}} \) \( [\sigma] \) | \( S_{\text{var, kol}} \) \( [\sigma] \) | \( E_{\text{thr}, \gamma} \) [TeV] | \( \Phi_{OG} \) \( [10^{-13} \text{ cm}^{-2} \text{s}^{-1}] \) |
|-----|----------|----------------------------------------|----------------|---------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1   | GRS1915  | 100 (1325)                             | 106,1 (1318,1) | 13,5    | **0,57** (0,19) | -2,19          | 1,92           | 20,3           | 1,8            |
| 2   | Cyg X-3  | 125 (1806)                             | 133,3 (1739,4) | 14,3    | **0,71** (1,56) | 1,43           | 0,75           | 20,6           | 1,5            |
| 3   | Geminga  | 114 (1128)                             | 101,1 (1092,0) | 27,6    | **1,24** (1,06) | -0,25          | 0,07           | 19,4           | 4,1            |
| 4   | AE Aqr   | 24 (151)                               | 16,0 (150,2)   | 14,5    | **1,83** (0,07) | -1,24          | -0,16          | 27,0           | 7,8            |
| 5   | Berk 87  | 162 (2017)                             | 142,2 (1885,2) | 36,8    | **1,60** (2,95) | -0,77          | -1,93          | 20,4           | 3,6            |
| 6   | SS433    | 81 (852)                               | 79,6 (832,9)   | 16,0    | **0,16** (0,65) | 1,66           | -0,25          | 22,8           | 2,3            |
| 7   | Cyg X-1  | 137 (1907)                             | 138,5 (1914,0) | 18,7    | **0,11** (-0,15) | -0,17          | -0,36          | 20,1           | 1,9            |
| 8   | Her X-1  | 156 (1624)                             | 117,4 (1602,5) | 54,9    | **3,33** (0,53) | 1,35           | 1,13           | 20,3           | 6,5            |
| 9   | AM Her   | 98 (1149)                              | 89,9 (1127,8)  | 22,3    | **0,82** (0,62) | 1,33           | 1,10           | 22,8           | 2,8            |
| 10  | V404 Cyg | 137 (1989)                             | 140,2 (1966,7) | 17,8    | **0,25** (0,49) | -2,00          | 0,21           | 20,1           | 1,8            |
Hybrid events: more reconstruction

- Expect sensitivity boost:
  - Scaled width cut and timing hadron rejection (Q~3)
  - Further g/h separation: Angular cut, length, … (+ more sophisticated methods)
  - Improved angular resolution from hybrid events: e.g. treat telescope as part of array (not yet simulated)
  - Consider time-development of image → independent direction reconstruction
Large zenith angle: outside HiSCORE viewcone

Telescope [0, 1, 2, 3]
Zenith angle = 41

Core distance

sim_telarray simulation, 2010
Test width scaling with IACT+HiSCORE “toy-MC-test”

- Full simulation sim_telarray
- 2D-lookup-table for MC-width $w_{\text{MC}}$ (core, size)
- MC-core randomized with HiSCORE resolution
- Use randomized core position for width scaling
Tunka HiSCORE Status

Optical station

Electronic box
Array Optimization HiSCORE

Simulation studies:
→ Large PMTs (12"")
→ Graded array layout
Gamma-hadron separation

Systematic bias

- **LDF & widths**: sensitive to whole shower
  Large overestimation for heavy particles (long tails)

- **Timing**: sensitive to specific point
  (edge time)
  Small overestimation for heavy particles
Particle separation

Lighter particles develop higher up in the atmosphere.
Particle separation (2)

Systematic Xmax difference
Time width and timing model

![Graph showing distributions for different types of particles (Gamma-rays, Protons, Iron nuclei).](image)
HiSCORE + IACTs
Timing array + imaging telescopes

Central reconstruction parameter: **Shower core position**

IACT image scaling using array core position

Monoscopic operation with larger distances btw telescopes

Increased area / telescope; Hybrid event reconstruction

Improvement of g/h separation \(x2-3\)

(also see Kunnas et al., this conference)
Milagro / HAWC

http://umdgrb.umd.edu/~bbbaugh/work/hawc.php
MGRO J1908+06

Assuming pevatron with cutoff at 3PeV

HiSCORE 10 km²
No µ det.
1 year (200h)
Tycho Supernova remnant

Assuming pevatron with cutoff at 3PeV

HiSCORE 100 km²
No μ det.
3 years
Absorption

**Galaxy**: 100TeV-PeV: e+e-pair production with low-E photons

- Interstellar radiation field
- Cosmic Microwave Background

(e.g. Moskalenko et al. 2006)
Absorption

Many Galactic sources:
Weak absorption up to 300 TeV

Universal feature:
Distance-dependent absorption above 300 TeV
Particle separation $X_{\text{max}}$ vs. $E$

![Graph showing the relationship between $X_{\text{max}}$ and reconstructed energy for different particle types. The graph includes data points and error bars for Gamma-rays, Protons, and Iron nuclei.]