The Tunka multi–component EAS detector for high energy cosmic ray studies

N. Budnev, Irkutsk State University
For Tunka - collaboration
April 17, 1912: In a balloon at an altitude of 5000 meters, Austrian scientist Victor Hess discovered "penetrating radiation" coming from space.

Even very well isolated gold-leaf electrosopes are discharged at a slow rate.
The bird’s eye view on a CR energy spectrum

\[ P(E) = A E^{-(\gamma + 1)} \]

CR Flux \((E) \times E^3\)

Fluxes of Cosmic Rays

- SNR, Pulsars...
- Galactic Cosmic rays ??
- AGN, GRB...
- Extragalactic Cosmic rays ??

Decays of super massive particles or topological defects???????
An extensive air shower (EAS) discovered by P. Auger (1938)

- Charged particles
- Cherenkov light
- Fluorescence light
- Radio emission

For electrons with $E_e > 25$ MeV $V_e > C/ n$

Atmosphere as a huge calorimeter
EAS Energy
\[ E = A \cdot [N_{ph}(200m)]^g \]
\[ g = 0.94 \pm 0.01 \]

Average CR mass A

\[ \text{Ln}A(E) \sim X_{\text{max}}(E) \]

\[ X_{\text{max}}(E) = C - D \cdot \log \tau(400) \]

\( \tau(400) \) - duration of a Cherenkov pulse at distance 400 m EAS core from

\[ X_{\text{max}}(E) = F(P) \]

\( P \) - Steepness of a Lateral Distribution Function (LDF)
1. Good energy resolution - up to 10% (probably 5% ?)
2. Good accuracy of $X_{\text{max}}$ measurement - 20 -25 g/cm$^2$
3. Good angular resolution - 0.1 – 0.3 deg
4. Low cost of an array:
The cost of Tunka-133 – 1 km$^2$ array is:
   0.5 $10^6$ Euro ( construction and deployment)
   + 0.2 $10^6$ Euro ( PMTs).
The cost of a Cherenkov EAS 100 km$^2$ array
   - about $10^7$ Euro

Disadvantage:

Short time of operation ( moonless, cloudless nights) – 5-10% of total time
Tunka Collaboration

Skobeltsyn Institute of Nucl. Phys. of Moscow State University, Moscow, Russia;

Institute of Applied Phys. of Irkutsk State University, Irkutsk, Russia;

B.K. Lubsandorzhiev, B.A. Shaibonov (ju), N.B. Lubsandorzhiev
Institute for Nucl. Res. of Russian Academy of Sciences, Moscow, Russia;

V.S. Ptuskin
IZMIRAN, Troitsk, Moscow Region, Russia;

Ch. Spiering, R. Wischnewski
DESY-Zeuthen, Zeuthen, Germany;

A.Chiavassa
Dip. di Fisica Generale Universita' di Torino and INFN, Torino, Italy.
Tunka-133 – 1 km² “dense” EAS Cherenkov light array

2009 year

Energy threshold \(10^{15}\) eV

Accuracy: core position \(\sim 10\) m
energy resolution \(\sim 15\%\)
\(\delta X_{\text{max}} < 25\) g∙cm\(^{-2}\)

50 km from Lake Baikal
2009 y. Tunka-133: 19 clusters, 7 detectors in each cluster.
Cherenkov light pulses of two detectors of a cluster located at a distance 700 m from EAS core.

1. ADC AD9430, 12 bit, 200 MHz
2. FPGA XILINX Spartan-3
2010-2012
Six outer clusters were deployed

175 optical detectors (EMI 9350) covering an area of 3 km$^2$

Angular sensitivity
Three seasons of array operation

2009 - 2010: 286 hours of good weather.
2010 – 2011: 305 hours of good weather.

> $6 \cdot 10^6$ events with energy $\geq 10^{15}$ eV.

Distribution of the number of hit clusters in an event.

Trigger counting rate during one night.

>10 events during every night with number of hit detectors more than 100.
Tunka-133 array with 6 distant external clusters

Statistics for 2009-2012 year

IN-events - core position inside circle: $R < 450\text{m}$
$>10^{16}\text{ eV}: 63490$
$>10^{17}\text{ eV}: 605$

Out-events - core position inside ring: $450\text{ m} < R < 800\text{ m}$
$> 10^{17}\text{ eV}: 1900$
Example of event: EAS energy $2 \cdot 10^{19}$ eV
The all particles energy spectrum $I(E) \cdot E^3$

$\gamma \sim 3.0$

$\gamma \sim 3.3$

$I(E) \sim E^{-\gamma}$

$\sim 3 \cdot 10^{17} \text{ eV}$
The energy spectrum in the range from $10^{16}$ to $10^{18}$ eV cannot be fitted with only one power law index:

- $3.21 \pm 0.01$ ($6 \cdot 10^{15} - 2 \cdot 10^{16}$ eV)
- $2.97 \pm 0.01$ ($2 \cdot 10^{16} - 10^{17}$ eV)
- $3.30 \pm 0.1$ ($3 \cdot 10^{17} - 10^{18}$ eV)
The primary CR mass composition changes from light (He) to heavy up to energy ~ 30 PeV.

A lightening of the mass composition takes place starting from an energy 100 PeV.
1. Cherenkov technique is very suitable way to study high energy cosmic rays as well gamma-rays. Tunka valley is one of the best place for construction of large Cherenkov EAS arrays.

2. The spectrum in the energy range of $10^{16}$ to $10^{18}$ eV cannot be fitted with single power law index. There is an indication on the second knee at $\sim 3 \cdot 10^{17}$ eV
   - $3.21 \pm 0.01$ ($6 \cdot 10^{15} - 2 \cdot 10^{16}$ eV)
   - $2.97 \pm 0.01$ ($2 \cdot 10^{16} - 10^{17}$ eV)
   - $3.30 \pm 0.1$ ($3 \cdot 10^{17} - 10^{18}$ eV)

3. Tunka spectrum is in a good agreement with KASCADE-Grande. The key problem – to increase an accuracy of absolute energy calibration. Is it possible to have 5% accuracy?

4. More statistics is necessary at the energy range of $10^{17} - 10^{18}$ eV. The Tunka-133 array will continue data taking for another 7-8 seasons.

5. Primary mass composition changes from the light (He) starting from “knee” energy to the heavy at $3 \cdot 10^{16}$ eV. The mass composition is still heavy at least up to $10^{17}$ eV. More statistics is necessary in the energy range $10^{17} - 10^{18}$ eV.
1. Skobeltsyn Institute of Nucl. Phys. of Moscow State University, Moscow, Russia;
2. Institute of Applied Phys. of Irkutsk State University, Irkutsk, Russia;
3. Institute for Nucl. Res. of Russian Academy of Sciences, Moscow, Russia;
4. IZMIRAN, Troitsk, Moscow Region, Russia;
5. DESY-Zeuthen, Zeuthen, Germany;
6. Dip. di Fisica Universita' di Torino and INFN, Torino, Italy.

7. A Haungs, F G Schroder, R Hiller, D.Kostunin
   Institut f¨ur Kernphysik, Karlsruhe Institute of Technology (KIT), Germany

8. M Kleifges, 1, O Kromer, C Ruhle,
   Institut f¨ur Prozessdatenverarbeitung und Elektronik, Karlsruhe Institute of Technology (KIT), Germany

8. D Besson, J Stockham, M Stockham
   Department of Physics and Astronomy, University of Kansas, USA

   Institut fur Experimentalphysik, Hamburg University, German

10. G.Rowell
    School of Chemistry and Physics, University of Adelaide, Australia

In 2013 year we are waiting new members of Tunka-collaboration
11. MPI (Munich, Germany), JINR (Dubna), Mephi (Moscow), ASU (Barnaul), IKFIA (Yakutsk)……
In near future we intend:

1. To supplement the Tunka-133 with a net of radio antennas [Tunka-REX (Radio Extension) array] in a first step for common operation with the Cherenkov array and then to explore of this novel detection technique for high energy CR studies.

2. To construct a net of large area detectors based on scintillation counters provided by the KASCADE-Grande Collaboration. To develop new and improve existing methods of CR studies and absolute calibration of the Tunka-133 array with joint measurements of Cherenkov and radio radiations as well as EAS charged component.

3. To deploy a fluorescent detector at 7-10 km distance from the Tunka-133 array for joint operation.

4. To create a non-imaging air shower array Tunka – HiSCORE (Hundred*km² Cosmic ORigin Explorer) with at least 10 km² area to explore the γ-ray sky beyond 10 TeV and cosmic rays with energy 100 TeV - 1 EeV.
Tunka Rex – Tunka Radio Extension

• At present time Tunka-Rex is an array of about 20 antennas, which covers an area of 1km$^2$. It measures the radio emission of cosmic-ray air showers above $10^{16}$ eV. It is triggered by the Tunka-133 array. The radio-Cherenkov-hybrid measurements thus offer a unique opportunity for a cross calibration of both calorimetric detection methods.

• The main goal of Tunka-Rex is to determine the precision of the radio reconstruction for the energy and mass composition of CR, and thus to experimentally test theoretical predictions that the radio precision can be similar to the precision of air-Cherenkov and fluorescence measurements. At the same time, Tunka-Rex can demonstrate that radio measurements can be performed on a large area for a relatively cheap price. Finally, radio-antenna arrays have the perspective to increase the effective observation time compared to air-Cherenkov and fluorescence detectors by an order of magnitude.
Registration of radio signals from EAS

Short Aperiodic Loaded Loop Antenna (SALLA)
(A.Haungs et al. Institute fur Kernphysick, Forschungszentrum, Karlsruhe, Germany

20 antennas SALLA were installed in autumn 2012

Antennas are connected to the free FADC channels of Tunka-133 cluster electronics
A lot of selected EAS radio candidates were found.

A radio pulse in both polarizations shortly before PMT signals
Detectors of charge EAS component

• In 2012 the University of Torino transferred scintillation counters of KASKADE-Grande for joint operation with the Tunka-133 array. It is planned to start deployment of scintillation stations for detection of EAS charged particles in summer of 2013. All together 24 stations will be installed 10 m² area each.

• It will allow to develop new and improve existing methods of studies of CR in the energy region of Galactic cosmic rays acceleration limits and absolute calibration of the Tunka-133 array with joint measurements of Cherenkov and radio radiations as well as EAS charged component.
2012 - 2013 years

More than 2000 events with $E > 3 \cdot 10^{16}$ eV per season

- 20 scintillation counters, 10 m$^2$
- 20 Radio antennas SALLA
Cross calibration of Cherenkov light and fluorescent light methods.

Image detector from TUS experiment
Mirror area is $S = 10 \text{ m}^2$
Field of view $\pm 7 \text{ deg}$
Gamma observatory

Tunka – HiSCORE

(Hundred* Square-km Cosmic Origin Explorer).

(More details: O.Gres’, Poster No.72)
For recent years gamma-astronomy became the most dynamically developing direction of high energy astro- physics. Gamma-radiation with energy higher than 1 TeV from more then 100 local sources has been detected.

Advantages of gamma-astronomy:
- gamma-quanta preserve the direction to the source;
- relative simplicity of $\gamma$-ray detection in comparison with neutrino.
To detect Ultra-High energy gamma-rays effective area of array must be 10 km$^2$ at least.

An Imaging ACT must have >10000 channels / km$^2$.

Cost of the IACT more than 100 millons $/ km^2$

An IAST is narrow-angle Telescope (3-5° FOV) consisting of a mirror of 4 -24 m diameter which reflects EAS Cherenkov light into a matrix of photosensors, in which EAS image is formed.
Tunka - HiSCORE (Hundred* i Square-km Cosmic Origin Explorer).

Non-imaging air Cherenkov array
Area: from 1 to 100 km²
Spacing between detector stations 100-200 m
Large Field of view: ~ 0.6 sr
~200 channels / km.
Total cost ~ 50 · millions Euro (for 100 km²)

- Cosmic-rays with energy: 100 TeV - 10 EeV
- Gamma-rays: \( E_\gamma > 10 \text{ TeV} \), up to PeV, ultra-high energy regime
- Particle physics: beyond LHC range
Tunka-HiSCORE optical station

4 PMTs

Calibration light source

rms <0.2 ns
Gamma-ray Astronomy

Search for the PeVatrons.
VHE spectra of known sources: where do they stop?
Absorption in IRF and CMB.
Diffuse emission: Galactic plane, Local supercluster.

Charged cosmic ray physics

Energy spectrum and mass composition from $10^{14}$ to $10^{18}$ eV.
$10^8$ events (in 1 km$^2$ array) with energy $> 10^{14}$ eV per one season (400 hours).

Particle physics

Axion/photon conversion.
Hidden photon/photon oscillations.
Lorentz invariance violation.
pp cross-section measurement.
Quark-gluon plasma.
Gamma-ray point-source survey sensitivity for Tunka-HiSCORE
(for statistics: 50 events or 5 RMS during $T = 500$ hours)

1 – 1 km$^2$, 4 x 8” PMTs per station

2 – 1 km$^2$, 4 x 12” PMTs per station + net of mirrors ($S = 2 \text{ m}^2$, ±7-10° FOV, without imaging)

2’ mounting of matrix in each mirror (not yet simulated)

3 = 2 plus 10$^4$ m$^2$ muon detectors

4 – 10 km$^2$, 4 x 8” PMTs per station

4’ – 10 km$^2$ for 12” PMT (not yet simulated)

5 – 100 km$^2$, 4 x 8” PMTs per station
What we can see with 1 km\(^2\) array (short list)

<table>
<thead>
<tr>
<th>Name</th>
<th>RA degrees</th>
<th>Decl</th>
<th>Flux at 1 TeV, 10^{-12} cm(^{-2}) s(^{-1}) TeV(^{-1}) (\Gamma)</th>
<th>Flux at 35 TeV, 10^{-17} cm(^{-2}) s(^{-1}) TeV(^{-1}) (from Milagro)</th>
<th>Time of observation per one year (x 0.5- wetter factor)</th>
<th>Number of events per one season E&gt; 20 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tycho SNR (J0025+641)</td>
<td>6.359</td>
<td>64.13</td>
<td>0.17 ±0.05 (\Gamma=1.95 \pm 0.5)</td>
<td>162.6 ±9.4</td>
<td>236h</td>
<td>88</td>
</tr>
<tr>
<td>Crab</td>
<td>83.6329</td>
<td>22.0145</td>
<td>32.6 ±9.0 (\Gamma=2.6 \pm 0.3)</td>
<td>110h,</td>
<td>680</td>
<td></td>
</tr>
<tr>
<td>SNR IC443 (MAGIC J0616+225)</td>
<td>94.1792</td>
<td>22.5300</td>
<td>0.58 ±0.12 (\Gamma=3.1 \pm 0.30)</td>
<td>28.8 ±9.5</td>
<td>112h,</td>
<td>2 – (from MAGIC) 50 ( from Milagro)</td>
</tr>
<tr>
<td>Geminga</td>
<td>98.50</td>
<td>17.76</td>
<td></td>
<td>37.7 ±10.7</td>
<td>102h,</td>
<td>80</td>
</tr>
<tr>
<td>M82 (Starburst Galaxy)</td>
<td>148.7</td>
<td>69.7</td>
<td>0.25 ±0.12 (\Gamma=2.5 \pm 0.6 \pm 0.2)</td>
<td></td>
<td>325h,</td>
<td>22</td>
</tr>
<tr>
<td>Mkn 421 (BL, z=0.031 Variable)</td>
<td>166.114</td>
<td>38.2088</td>
<td>50-200 (\Gamma=2.0-2.6)</td>
<td></td>
<td>140h</td>
<td>20 - 1000</td>
</tr>
<tr>
<td>SNR 106.6+2.7 (J2229.0+6114)</td>
<td>337.26</td>
<td>61.34</td>
<td>1.42 ±0.33 ±0.41 (\Gamma=2.29 \pm 0.33 \pm 0.30)</td>
<td>70.9 ±10.8</td>
<td>167h</td>
<td>140 ( from VERITAS 235 ( from Milagro)</td>
</tr>
<tr>
<td>Cas A (SNR, G111.7-2.1[6])</td>
<td>350.853</td>
<td>58.8154</td>
<td>1.26 ±0.18 (\Gamma=2.61 \pm 0.24 \pm 0.2)</td>
<td></td>
<td>177h</td>
<td>40</td>
</tr>
<tr>
<td>CTA_1(SNR,PWN)</td>
<td>1.5</td>
<td>72.8</td>
<td>1.3 (\Gamma=2.3)</td>
<td></td>
<td>266 h</td>
<td>200</td>
</tr>
</tbody>
</table>
In October 2012 3 HiSCORE optical stations were put in operation together with Tunka-133.
3 stations in October 2012

$S = 1\ \text{km}^2$, 60 stations, 150 m step, 240 PMTs (150 PMTs are available), 1 M Euro, 2012 – 2014

Decreasing of energy threshold

$S = 1\ \text{km}^2$, 60 station with 240 PMT (12") + 15 mirrors ($S = 2\ \text{m}^2$)
- Without matrix of PMTs
- With matrix of PMTs
Cost: 5 M Euro.

Increasing of area of array

$S = 10\ \text{km}^2$, 225 station, 200 m step, 1000 PMT, 5-6 M Euro.

Probably, choose new Place for deployment?

10000 m$^2$ scintillation detectors (1% of the whole area)
- 2-5 muons from 25 TeV protons

$S = 100\ \text{km}^2$, 2000 station, 1 PMT in station
10-12 M Euro
Tunka-HiSCORE
– 1 km² stage 1

150 m

9352KB
8”, ET
Tunka-HiSCORE – 1km² stage 1A

150 m

300 m

Installing of PMTs matrix, Image techniques

2 m² mirror, ±7° FOV,
Tunka : 2013-2014

Scintillation detectors
S = 8-10 m²

HiSCORE, stage 1

Tunka-133, 175 Cherenkov detectors

Radio antenna
Расстояние между детекторами 150 м

2015-2016 year

Tunka-HiSCORE, stage 2, S = 10 km²
1. In 2013 year Cherenkov Tunka-133 array will be supplemented with large scintillate detectors and a fluorescent light detector, so all components of EAS: Cherenkov, radio and fluorescent emission as well charge particles will be measurement in Tunka experiment.

2. In near future we intend to create the new Tunka-HiSCORE observatory with area at least 10 km² which will allow:

- To perform search for local Galactic sources of gamma-quanta with energies more than 20-30 TeV (search for PeV-trons) and study gamma-radiation fluxes in the energy region higher than 20-30 TeV at the record level of sensitivity.

- To study high energy part of gamma-rays energy spectrum form the most bright balzars (absorption of gamma-quanta by intergalactic phone, search for axion-photon transition).

- To study energy spectrum and mass composition of cosmic rays in the energy range of $5 \cdot 10^{13}$ - $10^{18}$ eV at so far unprecedented level of statistics.
Thank you!