Tunka-133 EAS Cherenkov Array: Status, First Results and Plans

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May 2009
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Search for Acceleration Limit of Galactic Sources

- Energy range $10^{16}$-$10^{18}$ eV
- need 1 km$^2$, smaller spacing than standard Auger
- need complementary techniques

- KASCADE-Grande terminated
- IceTop/IceCube 50% ready
- Tunka-133 (calorimetric) 70% ready
- Auger low energy extension planned

![Graph showing cosmic ray energies and locations of observatories]

CR from SNR to CR from AGN
Tunka-133 – 1 km² “dense” EAS Cherenkov light array

Energy threshold \( \sim 10^{15} \text{ eV} \)
Statistics for one winter (400 hours):
\( > 3 \cdot 10^{15} \text{ eV} \) – \( 5 \cdot 10^5 \) events
\( > 10^{17} \text{ eV} \) – \( \sim 300 \) events

Accuracy: core location \( \sim 6 \text{ m} \)
energy \( \sim 15\% \)
\( X_{\text{max}} < 25 \text{ g} \cdot \text{cm}^{-2} \)
$E_0 \sim Q_{175}$

$\ln A \sim X_{\text{max}}$

Methods of $X_{\text{max}}$ measurement:

1. Steepness of LDF: $P \sim H_{\text{max}}, \text{km}$

2. Signal duration $\sim$ 
   $\Delta X \text{ g/cm}^2$

   $\Delta X = X_0/\cos \theta - X_{\text{max}}$
Tunka-25 Results
(2000-2004)

QUSAR Tube
35 cm diameter photocathode

Area of array = 0.1 km²
Tunka-25: Usage of Cherenkov Light LDF for Reconstruction of EAS Parameters

1. Core position - \( x, y \)

2. Light flux at core distance 175 m - \( Q_{175} \)
   \[ E_0 = C \cdot Q_{175}^{0.95} \]

3. Steepness of LDF - \( P = \frac{Q(100)}{Q(200)} \)

Core distance range: 0 < \( R < 350 \) m
All particle spectrum

Flux $\times 10^{-6}$ m$^{-2}$s$^{-1}$ster$^{-1}$ (GeV)$^{-1.6}$

Energy per particle, GeV

Legend:
- ATIC
- TUNKA
- KASCADE
- TIBET
- JACEE
- SOKOL
- TIC
- HEGRA
Mean mass composition

\[ <\ln A > \]

Energy per particle, GeV

Data sets:
- ATIC
- TUNKA
- KASCADE
- JACEE
Tunka-133: 19 clusters, 7 detectors in each cluster

DAQ center

Optical cable

Cluster Electronic box

PMT EMI 9350 Ø 20 cm

S=0.88 km²
Cherenkov light pulses at two detectors of the cluster at core distance ~ 700 m

1. ADC AD9430, 12 bit, 200 MHz
2. FPGA XILINX Spartan-3

FADC developed in SINP MSU. Now we have 80 cards.

Tunka-133 is the first EAS Cherenkov light array with a pulse waveform registration by each detector.
Layout of Tunka-133 and time schedule of array deployment

2006 – first cluster

2007 – 4 clusters
Operation: 270 h of clean weather, 300,000 triggers

2008 – 12 clusters

2009 – 19 clusters (this autumn)
Deployment of the array

Optical cable

Detector installing

PMT preparing
October 2007- April 2008 ( four cluster in operation)

270 hours of data taking during clean moonless nights.

$\sim 3 \cdot 10^5$ events with energy more than $10^{15}$ eV.
Zenith-angular distribution

For $E > 7$ PeV
Low energy region

100 % efficiency
Inside the array geometry
for $E_0 > 2 \text{ PeV}$
Methods for the core reconstruction

• 1. Old: by using Lateral Distribution Function (LDF)

• 2. New: by using Width vs. Distance Function (WDF)

\[ \lg (\tau_{1/2}(R)) = 0.194 \left( \frac{400 - R}{500} \right) + \left( \frac{R+100}{500} \right) \lg(\tau_{1/2}(400)) \]

FWHM of signal at R m from the core

Only one varying parameter.
Event example: $E_0 = 3.8 \cdot 10^{17}$ eV

$\theta = 22.9^\circ$  
$X_{\text{max}} = 612 \text{ g\cdot cm}^{-2}$

$D \sim \lg(\text{light flux})$

$\lg(\text{FWHM/ns}) = a + b \cdot R$

WDF - Width vs. Distance Function
Another event: $E_0 = 1.5 \cdot 10^{17}$ eV

$\theta = 18.1$

$X_{\text{max}} = 583$ g·cm$^{-2}$

$\lg(\text{FWHM/ns})$
Is it possible to reconstruct EAS with core position outside the array geometry?

For $E > 5 \cdot 10^{17} \text{ eV}$

Effective area increases to 4 - 10 times

Lg(FWHM) $\sim R$

Very simple dependence!

Can we reach accuracy $\sim 20 \text{ m}$?

Experimental calibration and detailed simulation is needed.

1-2 clusters for Study WDF at Large distance

Tunka-133

0.5 km

1-1.5 km
Distant core event

Experiment – very preliminary.
Distant core event

Experiment – very preliminary.

LDF result

WDF fit
Distant core event

Experiment – very preliminary.

LDF result

WDF fit
Plan for Tunka-133 upgrading

- Scintillation muon counters
  \( E_0, X_{\text{max}} \) (from Tunka-133), \( N_\mu \)

- Radio-antennas.
Muon number vs. \(X_{\text{max}}\)

AIRES 2.8.4a
QGSJET-II

\(E_\mu > 1\) Gev, \(\theta = 0\)

\[\log N_\mu (\text{corr}) = \log N_\mu - \frac{X_{\text{max}} - 600}{1500}\]

- \(p\) (500 events)
- \(\text{He}\) (500 events)
- \(N\) (500 events)
- \(\text{Fe}\) (500 events)
Muon number vs. $X_{\text{max}}$ ($\delta N_\mu / N_\mu = 5\%, \ \delta X_{\text{max}} = 20 \text{ g/cm}^2$)

$E_\mu > 1 \text{ Gev}, \ \theta = 0$

$\text{AIRES 2.8.4a}$

$\text{QGSJET-II}$

$p$ (500 events)

$\text{He}$ (500 events)

$N$ (500 events)

$\text{Fe}$ (500 events)

$\text{lg} N_\mu$

$\text{lg} N_\mu (\text{corr}) = \text{lg} N_\mu - \frac{X_{\text{max}} - 600}{1500}$

$X_{\text{max}}$
Registration of radio signal from EAS

Aim:
1. Study of the accuracy of Radio-method with the data from Cherenkov array (Energy, core position, $X_{\text{max}}$).
2. Deployment the net (20-30) radio-antennas.
Data taking with DAQ Tunka-133

The first two antennas (D.Besson et al. University of Kansas, USA) at Tunka

Antennas were connected to free FADC channels of Tunka-133 electronic cluster
Cluster box
Optical detector
Water tank
Scintillation counter 8-10 m²
Data acquisition house

2011-2012
38 muon detectors + net of radio antennas

Accuracy of $N_\mu$ Reconstruction $\approx 5-10\%$
Conclusion

• More than 70% of detectors operated during the last winter season. Commissioning of the whole array is planned for the autumn 2009.

• The first results show the array parameters are in good agreement with expected ones. Recording of pulse waveform in each detector provides more reliable measurement of $X_{\text{max}}$ and open the possibility of reconstruction of EAS with core outside the array geometry.

• Work for the upgrading of Tunka-133 with day-time operating detectors (radio-antennas and scintillation counters) has begun.