Measurement of Ultra-high Energy Cosmic Rays

- First Results from Telescope Array (TA) -

May 7, 2010 @ ULB

M. Fukushima, ICRR, Univ. Tokyo
The Telescope Array (TA) Collaboration


~120 Scientists from Japan, US, Korea, Russia and Belgium
ICRR/Tokyo, Tokyo Tech., Osaka-City, Univ. of Utah, Rutgers, INR/RAS, ULB & others
Detection of Air Shower

**SD**: Surface Detector

1. **particle detection by surface array**

2. **Imaging by Fluorescence Telescope**

**FD**: Fluorescence Detector

- ~20 km

- ~1 km

- PMT camera

- Telescope

- Particle detector
~30 km

507 Surface Particle Detectors cover 680 km²

3 Fluores. Telescope stations overlook the array.

Utah, USA
39.3° N
112.9° W
Alt. 1400 m
Middle Drum telescope station
Transfer of HiRes – 1 and adjustment
One of the first events of TA: 2005/07/12, 2:52 am, Utah.

200 ns / step.

top / bottom & left / right of camera view reversed.
FD is a Total Absorption Calorimetry for absolute energy measurement.

   \( \Delta E \rightarrow \# \text{ of photons} \)

   loss of photons

3. Telescope Calib. 
   \# of ptotons \rightarrow ADC ch
Primary composition and Xmax
Example of FD Event

June 20, 08:18:21(UTC), trigger ID 0000169
TA Surface Detector (Plastic Scintillator)
Plastic Scintillator

3 m², 12 mm t
WLSF readout, 2 layers overlaid

1 MIP photo-electron distribution

mean = 23.6 std = 6.6

24 pe
Lifted by helicopter
\sim 510 \text{ kG}
$pN_{\text{AIR}} N' N_{\text{AIR}}$ interaction @ UHE

Hadron cascade

$\pi^+ : \pi^- : \pi^0$

$\gamma \gamma$

$\pi$ decay

$\pi^+ : \pi^- : \pi^0$

Gen. of $\mu \nu$

$\pi p \sim 20mb$

had $N_{\text{AIR}}$ int. @ $\sim 100$ GeV

$\sim 500mb$

Air Shower generation

Growth stops at critical energy
Air Shower Detection

Shower particles \( \mu, e, \gamma, \ldots \)

Detector Response by GEANT4

12mm plastic scint. x 2

1.0 – 1.6 mm t Fe x 4

Self Calibration by cosmic “\( \mu \)” @ 700Hz
Event "Side" View

Zenith ~ arcsine (ΔT / ΔX)

Event Top View

$X, Y =$ counter #

number = MeV energy deposit (av U+D)

~ 2.5 MeV for vertical mu
090122-225422
TH~38°

Peripheral muon hits

signature of Delayed neutron
nearly horizontal event
Event Reconstruction by SD

Geometry
* by core location + arrival timing

Energy $\propto$ energy deposit on the ground
? estimate of zenith attenuation

Composition by shower front curvature + muon

+ Flat acceptance, uniform exposure
- Abs. energy : by shower MC
Event Reconstruction by FD

Geometry (direction + distance)

* Monocular: 1 FD by angular speed
* Stereo: intersect of 2-3 FDs
* Hybrid: + SD timing (+ core location)

Energy $\propto$ # of detected photons, ? atmospheric transparency etc..

Composition by Xmax (shower max.)

- Variable acceptance (energy, angle, distance, weather…)
  & change of exposure (seasonal sky coverage)
+ Abs. energy: experimental
SD and FD of TA are independent. Each by itself is a complete detector.

Numerous cross checks possible.

(No Calib. & no detector monitor in this talk)
TA measures

**Primary Composition:** what is the UHECR?

**Spectrum:** dip and cutoff?

**Source + Anisotropy:** From where it is coming?

**UHE \( \gamma \) and \( \nu \): Exotic origin?

Today’s talk covers analyses of
- \( X_{\text{max}} \) by stereo FD (by Y. Tameda)
- Spectrum by FD/SD hybrid (by D. Ikeda)
- UHE \( \gamma \) limit (by G. Rubtsov)

- [SD spectrum]
- [LSS association, Point sources etc.]
- [UHE \( \nu \) search]
Greisen - Zatsepin - Kuzmin (GZK) Cutoff

$\gamma p \rightarrow \Delta (1232) \rightarrow \pi^0 p$ or $\pi^+ n$

$E = 10^{20} \text{ eV}$

$E \approx 0.8 \times 10^{20} \text{ eV}$

$0.6 \times 10^{-27} \text{ cm}^2$

$2.725 \text{ K}$

411 ph/cm$^3$

Cosmic rays exceeding $\sim 10^{20} \text{ eV}$ must have origins nearby
At the highest energy region

If particles are protons at $E > 10^{18}$eV, we may be observing pair creation dip (uncle) and pion production (GZK) cutoff.

by Berezinsky Jun08
Cen A
~ 4 Mpc

X-ray picture

Optical picture
- operation in stable
  \( \gtrapprox 95\% \)
  \( \gtrapprox 16k \) hours

- wLAN interference in early stage

- thunder storms in summer

- maintenance access in autumn

- low temperature & snow in winter
Full operation since Nov '07

- ≥ 2.5k hrs

Long Ridge remote operation since May '09

- ≥ 2.1k hrs
(1) FD Stereo Analysis for Xmax

BRM-LR Stereo Event

Event Selection
• Xmax within FoV
• Zenith Angle < 56°
• Shower Core in R=9.6km circle
• $E > 10^{18.6}$eV
• good $\chi^2$

Check with MC expectation
Existing Xmax data

HiRes: stereo FD

Auger: FD/SD hybrid

\[
\langle X_{\text{max}} \rangle \quad \text{(g/cm}^2\text{)}
\]

\[
\log_{10}E \quad (\text{eV})
\]

Xmax by MC (Raw)
Example of Stereo Event

<table>
<thead>
<tr>
<th>Zenith</th>
<th>Azimuth</th>
<th>Core [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.23°</td>
<td>145.9°</td>
<td>0.09, -6.10</td>
</tr>
</tbody>
</table>
Reconstruction

1) Core and Direction by Stereo Geometry
2) E and Xmax by Inverse MC

Accuracy @ $10^{19}$eV
- Direction: < 1.6 deg
- shower core location: ± 180 m
- Energy: -5.4 ± 5.8 %
- Xmax: -9.7 ± 16 g/cm²
Making Simulated Events

Shower Simulation
- CORSIKA v6.9
- Hadronic Int. Model
  - QGSjet-II, QGSjet-01, SIBYLL
- Proton or Fe Nuclei
- Energy:
  - $\log E = 18.5-19, 19-19.5, 19.5-20$
  - Power index : - 3.1
- Zenith Angle : 0 – 60 deg
- thinning factor : $10^{-4}$
- Ecut: EM:100keV, hadron:100MeV
- Core: $r < 10$ km
- Each 500 events

Detector Simulation
- Atmosph. by nearby Radio Sonde
- Typical measured Mie attenuation by lidar ($h=1.0\text{km}$, $\lambda = 29\text{km}$)
- Fluorescence yield
  - Normalization by Kakimoto et al.,
  - Spectrum by FLASH
Psi angle (deg)

MC: CORSIKA QGSjet-II proton E^{-3.1}

Cuts:
E > 10^{18.6}\text{eV}
\theta < 56^\circ
Rp (km)

Preliminary

BRM

Preliminary

LR
Xmax “bias” by recon. + selection
Xmax “bias” by reconstr. + selection

![Graph showing reconstructed Xmax vs. log(Reconstructed E[eV]) for different models and materials.](image)
Comparison of reconstructed $X_{\text{max}}$ between data and MC

| $E > 10^{18.6}$ eV |

<table>
<thead>
<tr>
<th></th>
<th>QGSJET-II</th>
<th>QGSJET-01</th>
<th>SIBYLL</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>1.44</td>
<td>1.046</td>
<td>1.63</td>
</tr>
<tr>
<td>Fe</td>
<td>55.54</td>
<td>56.67</td>
<td>85.71</td>
</tr>
</tbody>
</table>

Chi$^2$/dof
<Reconstructed Xmax> vs. E

Preliminary
Chi2 vs shift of dXmax
(2) Hybrid Analysis for Spectrum

- FD geom. reconstr. with SD timing
- Energy determined by FD
- Acceptance determined by “SD”

Example of hybrid event
**Geometrical reconstruction**

**Mono reconstruction**

\[ t_i = t_{\text{core}} + \frac{1}{c} \frac{\sin \psi - \sin \alpha_i}{\sin(\psi + \alpha_i)} r_{\text{core}} \]

**Hybrid reconstruction**

\[ t_i = t_{\text{core}} + \frac{1}{c} \frac{\sin \psi - \sin \alpha_i}{\sin(\psi + \alpha_i)} r_{\text{core}} + t_{\text{SD}} \left( \frac{r_{\text{core}} - r_{\text{SD}}}{c} \right) \cos \psi \]

**FD mono analysis + timing of one (best) SD**

### Fitting Results
- \( \psi = 1.513 \pm 0.001 \) [rad]
- \( r_{\text{Core}} = 17.763 \pm 0.004 \) [km]
- \( t_{\text{Core}} = -16115.817 \pm 0.000 \) [ns]
- \( \chi^2/\text{ndf} = 14.193 \)

### Geometry Results
- \( \text{zen} = 3.909 \) [deg]
- \( \text{azi} = 313.053 \) [deg]
- \( \text{core} = (0.253, -6.162, 0.000) \) [km]
- \( r_p = 17.732 \) [km]
Shower profile reconstruction

- $X_{\text{max}}$ has to be observed
- Energy $> 10^{18.65}\text{eV}$
- Zenith angle $< 45$ degree
**MC simulation**

**Air shower simulation: COSMOS**

- **Items**
  - **Values**
    - Primary energy: $10^{18} \text{eV} \sim 10^{20.5} \text{eV}$
    - Zenith angle: $\cos \theta = 0.65 \ (\approx 50\text{degree}) \sim 1$
    - Primary particle: Proton
    - Thinning ratio: $10^{-4}$ ($\leq 10^{20} \text{eV}$), $10^{-5}$ ($> 10^{20} \text{eV}$)
    - Interaction model: QGSJET II
    - Cut threshold: 100keV

**SD**
- Time dep. Calib.
- Same as SD analysis

**FD**
- Time dep. Calib.
- BG by real data.
- Geom. corrected by star.
- Measured atmosphere

**Hybrid MC data:**
- Date: Random in FD observation period
- Core: 25km radius from CLF
- Slope data: $\sim 2.5M$ events with $E^{3.1}$
- Flat data: $\sim 20k$ events for each energy

**Missing energy**
- $\sim 8\%$
- $1\%$
Resolution (Geometry)

SDP Resolution (68%): ~0.4 deg

Arrival direction Resolution (68%): 1.1 deg

Core position Resolution (68%): ~200m

Psi RMS: 1.4 deg

Rp Resolution (68%): ~1%
The aperture is calculated from MC simulation.
Exposure: $\sim 3 \times 10^{15} \text{ m}^2 \text{ sr s} (>\sim 10^{19}\text{ eV})$
Data/MC comparison - 1

- BR station
- Filled circles: data
- Histograms: MC

- # of SDs vs number of the clustered SD
- # of selected FD PMTs vs number of selected PMTs
- # of p.e. / track length vs # of p.e. / track length [degree]
- \( \Psi \) angle vs \( \Psi \) [degree]
- Distance from core vs rCore [km]

- BR station
- Filled circles: data
- Histograms: MC
Data/MC comparison - 2

[Graph showing distribution of $X_{\text{max}}$]

[Graph showing distribution of energy]
Energy spectrum

Systematic errors

<table>
<thead>
<tr>
<th>Item</th>
<th>Systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescence yield</td>
<td>12%</td>
</tr>
<tr>
<td>Detector</td>
<td>10%</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>11%</td>
</tr>
<tr>
<td>Primary particle mass</td>
<td>5%</td>
</tr>
<tr>
<td>MC correction</td>
<td>3%</td>
</tr>
<tr>
<td>Total</td>
<td>19%</td>
</tr>
</tbody>
</table>
(3) UHE Photon Search

Shower front curvature

**deep shower maximum = curved front**
Example of front curvature
Event reconstruction

- Joint fit of LDF and shower front profile
- 7-parameters:
  - $x_{\text{core}}, y_{\text{core}}$ – shower core location at the ground level
  - $\theta, \phi$ – zenith and azimuthal angles of primary arrival direction
  - $S_{800}$ – normalization factor for LDF (corresponds to scintillation signal density at 800 meters)
  - $t_0$ – arrival time for the shower core
  - $a$ – dimensionless Linsley’s curvature parameter

\[
t(r) = t_0 + t_{\text{plane}}(r) + a \ t_L(r)
\]
\[
t_L(r) = \left(\frac{r}{39m}\right)^{1.5} \ LDF(r, \theta)^{-0.5}
\]
\[
S(r) = S_{800} \ LDF(r, \theta), \quad LDF(800m, \theta) = 1
\]

$LDF(r)$ – modified AGASA function

$r$ – core distance in shower plane
Linsley curvature “a”: data vs. photon MC

$0^\circ - 30^\circ$

$30^\circ - 45^\circ$

$45^\circ - 60^\circ$

$E_\gamma > 10^{19} \text{ eV}$

data

photon MC, $E^{-2}$ spectrum

Corsika with QGSJET-II

Larger curvature
Example of analysis of one event

$\theta = 59.9^\circ$, $E_\gamma = 3.2 \times 10^{19}$ eV, $C = 0.26$
C distribution: data vs photon MC

$s_{0^\circ - 30^\circ}$

$s_{30^\circ - 45^\circ}$

$s_{45^\circ - 60^\circ}$

$E_\gamma > 10^{19} \text{ eV}$

**data** photon MC, $E^{-2}$ spectrum

C is distributed uniformly between 0 and 1 for photon events.
Photon Flux Limit Conclusion

- $E_\gamma > 10^{19}$ eV
- $45^\circ < \theta < 60^\circ$
- $C > 0.5$
  - One event remain.
- Total exposure:
  - $158\text{km}^2 \text{sr yr}$
- $F_\gamma < 3.3 \times 10^{-2} \text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1}$
  (95\%CL) preliminary
SUMMARY

TA measures

Primary Composition: what is the UHECR?  
Spectrum: dip and cutoff?  
Source + Anisotropy: From where is it coming?  
UHE $\gamma$ and $\nu$: Exotic origin?  

Today’s talk covered  
• $X_{\text{max}}$ by stereo FD ---------------  
  ~ proton for $E=10^{18.5} \sim 10^{19.3}$ eV  
• Spectrum by FD/SD hybrid ----  
  ~ consistent with HiRes  
• UHE $\gamma$ limit ------------------------  
  ~ no $\gamma$ $E<10^{19}$ eV  

• [SD spectrum]  
• [LSS association, Point sources etc.]  
• [UHE $\nu$ search]  

Coming soon