The Cosmic Ray Energy Spectrum between 2 PeV and 2EeV Observed with the TALE Detector in Monocular Mode.

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Presented by Charlie Jui  
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Paris, France

Tareq’s son Ziad from Jerusalem, Oct 8
Telescope Array collaboration


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TA Low Energy Extension (TALE)

10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

Infill surface detector array of more densely packed surface detectors (lower energy threshold)
• All 10 TALE FD telescopes installed in 2013.
  – Shake-down 2013-2014
  – Stable operation since fall 2014
• 103 TALE SD counters deployed as of fall 2017
TALE Fluorescence Detector

- 10 high-elevation telescopes at the Middle Drum site, looking from $31^\circ$-$59^\circ$ in elevation.
- Originally designed for monocular and hybrid observations down to $\sim 10^{16.5}$ eV.

Expected TALE hybrid events per year
Combined Tim-Profile Fit

Shower Profile

- Signal
- MC Fit
- Scin
- Rayl
- Aero
- Cher

log₁₀(E) = 20.
Χ_max = 764.
N_max = 8.44e+6

From Top of Atmosphere

Slant Depth X

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For TALE FD reconstruction: we combined the time and profile fit: simultaneous Profile Constrained Geometry Fit (PCFG) originally developed for HiRes monocular analysis.

TALE FD Event

\[ \chi^2 / \text{ndf} = 6.561 / 65 \]
\[ T_0 = -10.28 \pm 0.5691 \]
\[ R_p = 7435 \pm 352.1 \]
\[ \psi = 55.58 \pm 4.237 \]

\[ \log_{10}(E) = 17.88 \]
\[ \chi_{\text{Max}} = 752.86 \]
\[ N_{\text{Max}} = 4.87 \times 10^8 \]
TALE Cherenkov Event

PCGF turns out to work very well on Cherenkov light dominated events

Shower Profile

\[ \chi^2 / \text{ndf} \quad 62.80 / 46 \]
\[ \log_{10}(E) \quad 17.50 \]
\[ X_{\text{Max}} \quad 538.55 \]
\[ N_{\text{Max}} \quad 2.16 \times 10^8 \]
Cherenkov light dominated events allowed TALE to reach more than another decade lower in energy than designed: Down to $10^{15.3}$ eV
Events

Between June 2014 and March 2016 TALE collected
220 173 events between $10^{15.5}$ and $10^{16.0}$ eV
98 677 events between $10^{16.0}$ and $10^{16.5}$ eV
23 285 events between $10^{16.5}$ and $10^{17.0}$ eV

Cherenkov dominated events (C'kov > 75% of total)

Fluorescence dominated events (Scin. > 75% of total)

Mixed signal events
Verification of monocular $\Psi$ resolution

Čerenkov

$logE>16.5$

Čerenkov

TALE Č'kov mono - hybrid psi comparison

Čerenkov

Mono – hybrid (w/ 16 SD)
Exposure

- TALE FD data collected from 06/20/2014 to 03/31/2016 (22 months).
- Only good weather data:
- **Total on-time 1080.0 hours.**
Composition?

Initial Assumption

primary fractions (H4a CR composition model)

- proton
- helium
- CNO
- MgSi
- Iron

Originally assumed H4A Composition (interpreted using QGS_jet II.3) gives an Xmax distribution appeared to be too high in the sky.

Adjusted Xmax dist. (a 4-component fit to QGS-Jet II.3) to better match TALE FD data: call this Tale Xmax Fit (TXF)
MC/Data Comparison

Validation of Aperture Calculation

Impact parameter: $R_p$ (km) (data)

Čerenkov

Mixed

Fluorescence

Zenith Angle: $\theta$

H4A

TXF
Consistency

Spectra obtained from the three classifications of events appear to be consistent
TALE Spectrum

break point $17.04 \pm 0.03$

break point $16.22 \pm 0.02$

slope: $-3.12 \pm 0.01$  $-2.92 \pm 0.01$  $-3.19 \pm 0.02$

fit $\chi^2 / \text{ndf} = 31.6 / 39$
TALE Spectrum

Break point: 17.04 ± 0.03

Break point: 16.22 ± 0.02

Slope: -3.12 ± 0.01
Slope: -2.92 ± 0.01
Slope: -3.19 ± 0.02

$\chi^2 / \text{ndf} = 31.6 / 39$

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Comparison to other experiments

TALE Spectrum compared to some recent Measurements

- TALE Monocular (2017)
- Yakutsk-Cherenkov (2013)
- Tunka-55 (2013)
- Tunka-133 (2013)
- KASCADE-Grande (2012)
- ICETOP (2016)
Summary

• We have measured the cosmic ray energy spectrum in the range $10^{15.3}-10^{18.3}$ eV
  – Published 2018 September 24. The Astrophysical Journal, Volume 865, Number 1
  – Three spectral features are seen: Knee, “dip”, “second knee” at energies at $10^{15.6}$ eV, $10^{16.22}$ eV and $10^{17.04}$ eV
  – The energies of the three features are approximately in the ratio of 1:4:26 (proton: beryllium: iron)

• Composition results in the near future

• TALE surface detector now operational
  – FD to SD trigger now running
Reserve Slides
# Systematic Errors

**Table 5.** Estimates of systematic uncertainties in the TALE FD energy scale and spectrum measurement. This uncertainty is approximately constant as a function of energy. [Explanation of change: Added entry: Cherenkov model]

<table>
<thead>
<tr>
<th>Energy</th>
<th>Source</th>
<th>Value</th>
<th>Contribution to Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 10^{17}$ eV</td>
<td>photonic scale</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>$&lt; 10^{17}$ eV</td>
<td>missing energy</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>$&lt; 10^{17}$ eV</td>
<td>atmosphere</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$&lt; 10^{17}$ eV</td>
<td>Cherenkov model</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>$&lt; 10^{17}$ eV</td>
<td>fluorescence yield</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$&lt; 10^{17}$ eV</td>
<td>composition ($X_{\text{max}}$)</td>
<td>3%</td>
<td>6%</td>
</tr>
<tr>
<td>$10^{18}$ eV</td>
<td>photonic scale</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>$10^{18}$ eV</td>
<td>missing energy</td>
<td>5%</td>
<td>10%</td>
</tr>
<tr>
<td>$10^{18}$ eV</td>
<td>atmosphere</td>
<td>2%</td>
<td>4%</td>
</tr>
<tr>
<td>$10^{18}$ eV</td>
<td>Cherenkov model</td>
<td>0</td>
<td>0</td>
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<td>6%</td>
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<tr>
<td>$&lt; 10^{17}$ eV</td>
<td>total</td>
<td>15%</td>
<td>31%</td>
</tr>
<tr>
<td>$10^{18}$ eV</td>
<td>total</td>
<td>15%</td>
<td>31%</td>
</tr>
</tbody>
</table>
Outline

• Introduction to TALE
• TALE Events and Reconstruction
• Detector Resolutions
• Aperture and Data/MC Comparisons
• Spectrum
• Interpretation of Spectrum
• Continuing work on TALE FD and SD
“Reconstruction” of an air shower

Event Display showing pattern of hit pixels

Direction of hit pixels fitted to a shower-detector plane (SDP)
Arrival times of signal light in each pixel is fitted as a function of the SDP $\theta$ angles: **Gives direction of primary cosmic ray**

\[ t_i = t_0 + \frac{R_P}{c} \tan \frac{\theta_i}{2} \]
SDP $\theta$ angles converted to slant depth.
Light signal fitted to depth to give energy $E$ and $X_{\text{max}}$ (depth of maximum)
TA Energy Spectrum

TALE Spectrum with Spectra of TA-SD and Auger (Rescaled Energy)

$E^3 J \left[ \text{eV}^2 \text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \right]$

$\log_{10}(E/\text{eV})$

- TALE Monocular (2017)
- TA BR/LR Monocular (2015)
- TA SD 7 year (ICRC 2015)
- Auger (2013) Rescaled +10%
Dependence on Xmax Distribution

- blue: iron
- green: H4a + HiRes/MIA
- black: TXF
- red: proton
Reconstruction Resolution (1/2)

Ψ Angle

Čerenkov

logE>16.5

Čerenkov

Mixed

Fluorescence

RP

Čerenkov

logE>16.5

Čerenkov

Mixed

Fluorescence

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Reconstruction Resolution (2/2)

$X_{\text{MAX}}$

Čerenkov

$\log E > 16.5$

Čerenkov

Mixed

Fluorescence

Energy

Čerenkov

$\log E > 16.5$

Čerenkov

Mixed

Fluorescence

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TALE “Infill” Surface Detector

- Construction and deployment funded by the Gov’t of Japan
- Add infill array (400m and 600m spacing) for hybrid and stand-alone observation.
- Also add counters to build out main TA SD array (1200m separation).
TALE Deployment: Summer 2017

- 103 counters are in place as of fall, 2017
- TALE SD is in shake-down mode
event duration (µs) (data)

Entries 392758
Mean 0.2228
RMS 0.118
event duration ($\mu s$) (data)

- Entries: 3726
- Mean: 1.416
- RMS: 0.7152
Figure 13: Total event duration (µs), for Cherenkov (left), Mixed (center), and fluorescence events (right). Black points are data, blue / red histograms are MC with mixed composition (H4a / TXF respectively).
Tracklength (deg) (data)

Entries 392758
Mean 8.642
RMS 2.6
Figure 14: Angular track-length (deg), for Cherenkov (left), Mixed (center), and fluorescence events (right). Black points are data, blue / red histograms are MC with mixed composition (H4a / TXF respectively).
Figure 19: Ratio of calorimetric energy to total shower energy as given by Conex simulations. Simulation sets of mono-energetic showers were used to calculate the ratio. Each point in the figure represents a simulation set and the curves represent a 4-th degree polynomial fit to the point.