TELESCOPE ARRAY: LATEST RESULTS

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for the Telescope Array Collaboration

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Outline

Telescope Array detector

Spectrum

Composition

Anisotropies
  Global distributions
  Hot spot
  Correlation with LSS
  Other searches

TA extension

Summary
UHECR experiments

- HiRES 1998 - 2006
- Telescope Array 2008 - now
- Yakutsk Array 1973 - now
- AGASA 1990-2004
- Pierre Auger Observatory 2004 - now
TELESCOPE ARRAY COLLABORATION


~140 collaborators in 5 countries:
Japan, USA, Korea, Russia, Belgium
TELESCOPE ARRAY DETECTOR
TELESCOPE ARRAY HYBRID DETECTOR

- 507 scintillator detectors covering 680 km²
- 3 fluorescence sites, 38 telescopes
- Surface detector fully operational from March 2008
- SD relative size: $\text{TA} \sim 9 \times \text{AGASA} \sim \text{PAO/4}$
TA surface detectors

- Deployed with the spacing $\sim 1.2$ km
- Powered by solar panels. Connected by radio.
TA Fluorescence Detectors

Refurbished from HiRes

Observation started Dec. 2007

Middle Drum

14 cameras/station
256 PMTs/camera

5.2 m²

~30 km

Observation started Nov. 2007

New FDs

256 PMTs/camera
HAMAMATSU R9508
FOV~15x18 deg
12 cameras/station

~1 m²

~112°52'00" W 112°52'00" W
113°03'00" W 113°03'00" W

Long Ridge

Black Rock Mesa

Observation started June 2007

6.8 m²
Hybrid event example

**Triple FD Event** (2008-10-26)

<table>
<thead>
<tr>
<th></th>
<th>$\theta$ [deg]</th>
<th>$\phi$ [deg]</th>
<th>$X$ [km]</th>
<th>$Y$ [km]</th>
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</thead>
<tbody>
<tr>
<td>MD mono</td>
<td>51.43</td>
<td>73.76</td>
<td>7.83</td>
<td>-3.10</td>
</tr>
<tr>
<td>BR mono</td>
<td>51.50</td>
<td>77.09</td>
<td>7.67</td>
<td>-4.14</td>
</tr>
<tr>
<td>Stereo BR&amp;LR</td>
<td>50.21</td>
<td>71.30</td>
<td>8.55</td>
<td>-4.88</td>
</tr>
</tbody>
</table>
Low energy extension (TALE)

- 10 additional telescopes of 100° in azimuth, 31° – 59° in elevation
- denser array of scintillators
- observational modes:
  - fluorescence light
  - hybrid mode
  - direct Cherenkov light
- lower energy threshold
Low energy extension (TALE)

Objectives: study the $10^{16}$ and $10^{17}$ eV decades with a hybrid detector.

- rigidity-dependent cutoff that starts with the knee at $\sim 3 \times 10^{15}$ eV
- the second knee
- the galactic-extragalactic transition
- $p - p$ and $p - \text{air}$ cross section between LHC and UHECR range $\gtrsim 10^{19}$ eV

All with a single experiment: TA + TALE
TA spectrum

TA measures spectrum by several techniques:

- Fluorescence detector (FD-mono) – at three stations independently + in stereo mode (FD-stereo)
- Surface detector (SD) – largest statistics
- Hybrid (SD+FD) – used for calibration
- Cherenkov light TALE – lowest threshold
- All spectra agree after rescaling of SD energies down by 1.27
TA spectrum

TA SD

$E^3 \times J \left[ \text{eV}^2 \times \text{m}^{-2} \times \text{sr}^{-1} \times \text{s}^{-1} \right]$ vs $\log_{10}(E/eV)$

- TA SD 7 year (ICRC 2015)
TA spectrum

TA SD + FD mono

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

\[
\begin{align*}
\log_{10}(E/\text{eV}) & \\
16 & - 20
\end{align*}
\]

- TA SD 7 year (ICRC 2015)
- BR-LR Mono 7 year (ICRC 2015)
TA spectrum

TA SD + FD mono + TALE FD

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

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

- TA SD 7 year (ICRC 2015)
- BR-LR Mono 7 year (ICRC 2015)
- TALE Bridge (ICRC 2015)
TA spectrum

TA SD + FD mono + TALE FD + TALE Čerenkov
Fit with a broken power law:

\[ E^3 J \left( \text{eV}^2 \times \text{m}^{-2} \times \text{s}^{-1} \times \text{s}^{-1} \right) \]

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>const</td>
<td>(0.399 \pm 0.095 \times 10^{27})</td>
</tr>
<tr>
<td>(p_{-1})</td>
<td>(-3.132 \pm 0.001)</td>
</tr>
<tr>
<td>(p_{-2})</td>
<td>(-2.94 \pm 0.02)</td>
</tr>
<tr>
<td>(p_{-3})</td>
<td>(-3.226 \pm 0.007)</td>
</tr>
<tr>
<td>(p_{-4})</td>
<td>(-2.66 \pm 0.02)</td>
</tr>
<tr>
<td>(p_{-5})</td>
<td>(-4.7 \pm 0.6)</td>
</tr>
<tr>
<td>(E_{1})</td>
<td>(16.34 \pm 0.04)</td>
</tr>
<tr>
<td>(E_{2})</td>
<td>(17.30 \pm 0.04)</td>
</tr>
<tr>
<td>(E_{3})</td>
<td>(18.72 \pm 0.02)</td>
</tr>
<tr>
<td>(E_{4})</td>
<td>(19.80 \pm 0.05)</td>
</tr>
<tr>
<td>(E_{1/2} \text{ Berezinsky})</td>
<td>(19.78 \pm 0.05)</td>
</tr>
<tr>
<td>(P_{\text{Chance GZK}})</td>
<td>(3.1e-11 \ (6.5 \sigma))</td>
</tr>
</tbody>
</table>
TALE spectrum

TALE spectrum: improvement since ICRC 2015

![TALE Energy spectrum (Ckov+Scin)](image)
TA spectrum

Fit with a broken power law:

$\log_{10} E_{\text{br}} = 17.32 \pm 0.05$

$\log_{10} E_{\text{br}} = 16.20 \pm 0.02$

$\gamma_1 = 3.19 \pm 0.01$

$\gamma_2 = 2.94 \pm 0.01$

$\gamma_3 = 3.22 \pm 0.01$

- TALE FD 1yr (PRELIMINARY)
- TA SD 7 year (ICRC 2015)
Comparison to other experiments

**Graph:**

- **Legend:**
  - $\triangle$ HiRes-I (2008)
  - $\triangledown$ HiRes-II (2008)
  - $\diamondsuit$ Yakutsk Cherenkov (2013)
  - $\blacktriangle$ Tunka-55 (2013)
  - $\blacktriangledown$ Tunka-133 (2013)
  - $\triangleleft$ KASCADE-Grande (2011)
  - $+$ Auger (2013)
  - $\Delta$ ICETOP (2013)
  - $\bullet$ TA Combined (ICRC 2015)

**Axes:**
- $E^3 \times J \ [eV^2 \times m^{-2} \times s^{-1} \times s^{-1}]$
- $\log_{10}(E/\text{eV})$
Spectrum summary

- Measurement of the spectrum over 4.7 decades with a single experiment (from $E = 10^{15.6}$ eV upward)
- Four features:
  - flattening ($E = 10^{16.34}$ eV)
  - 2nd knee ($E = 10^{17.3}$ eV)
  - ankle ($E = 10^{18.72}$ eV)
  - GZK break ($E = 10^{19.8}$ eV)
- Ankle and GZK break energies consistent with protons
- Discrepancy with Auger at highest energies
COMPOSITION
TA composition measurement

- Observable sensitive to composition: shower depth $X_{\text{max}}$
  - $X_{\text{max}}$ from FD data only
- Difficult measurement:
  - large fluctuations
  - limited statistics
  - biases in event selection
- TA strategy:
  - full MC simulation of the data analysis chain (including event selection)
  - prediction for different compositions
  - comparison to data
MD/SD hybrid analysis

- 7 years MD/SD Hybrid data, 623 events with $E > 10^{18.4}$ eV
- Pattern recognition cuts
- $X_{\text{max}}$ resolution is 22 g/cm$^2$

TA stereo analysis

- 8 years all FD stations, 1347 events with $E > 10^{18.4}$ eV
- $X_{\text{max}}$ resolution is 19 g/cm$^2$

**PRELIMINARY**
BR/LR hybrid analysis

- 7 years BR/LR hybrid, 2597 events with \( E > 10^{18.4} \) eV
- systematics \( \sim 20 \text{ g/cm}^2 \) (pink band)
- \( X_{\text{max}} \) resolution is 17 g/cm\(^2\)
$X_{\text{max}}$ distributions: data-MC comparisons
Comparison with Auger

- Face-value comparison appears to show a difference:

![Graphs showing comparison of data and models for X_max versus energy for different elements and models.](image-url)
TA-Auger composition WG

- Take Auger “composition mix” and pass it through complete TA simulation chain (including all detector biases)
- Compare to TA data → compatibility?
Photon limit

- Combine several photon-sensitive parameters into a single variable $\xi$ by Boosted Decision Trees (BDT) technique.
Composition summary

- TA excludes heavy composition (iron)
- protons do fit the composition measurements
- light mix cannot be excluded either
- contradiction with Auger may be not so dramatic as it appears
- improved limits on photons
ANISOTROPIES
Anisotropy data set (SD)

- covers the period 12.05.2008 — 11.05.2015 (full 7 years)
- zenith angle up to 55°, loose border cut
- geometrical acceptance; exposure $\sim 8700$ km$^2$ yr sr
- 2996 above 10 EeV
- 210 above 40 EeV
- 83 above 57 EeV
- angular resolution: better than 1.5°
- energy resolution: $\sim 20\%$
GLOBAL DISTRIBUTIONS
Comparison with isotropic distribution by KS test

- Low energy sets
  \(E > 10\) EeV and
  \(E > 40\) EeV are compatible with isotropy; the smallest KS p-value is 0.12.

- \(E > 57\) EeV

<table>
<thead>
<tr>
<th>Frame</th>
<th>longitude</th>
<th>latitude</th>
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</thead>
<tbody>
<tr>
<td>Equatorial:</td>
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<td>0.04</td>
</tr>
<tr>
<td>Supergalactic:</td>
<td>0.01</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Equatorial:

Supergalactic:
AUTOCORRELATION FUNCTION

- count number of pairs separated by the angle $\delta$
- compare to isotropic distribution; plot $p$-value as a function of the separation angle

- compatible with isotropy at $E > 10$ EeV and $E > 40$ EeV
- tension with isotropy at $E > 57$ EeV
HOT SPOT

- Reconstruction with even looser cuts optimized for statistics (72 events above 57 EeV in 5 yr).
- “Hot spot” within the circle of radius 20° centered at RA = 146°, Dec. = 43°.
- After accounting for arbitrary position and opening angles 15°, 20°, 25°, 30°, 35° the significance is 3.4σ post-trial (5.1σ pre-trial).
HOT SPOT: 7 yr update

Same cuts as for 5yr; 109 events with $E > 57$ EeV in 7yr set

5-year data
6 & 7th-year data (37 events)
HOT SPOT: 7 yr update

Significance Map (Li-Ma) 7 years

Oversampling with 20°-radius circle

Dec. (deg)

360

30

-30

60

R.A. (deg)

180

30

-60

E > 57 EeV

Preliminary
HOT SPOT: 7 yr update

Significance (same procedure as for 5 yr):

- oversampling at 15°, 20°, 25°, 30°, 35°, moving center

- Pre-trial: $P = 5.07\sigma$; $N_{on} = 24$; $N_{bg} = 6.88$;
  Post-trial $P = 3.7 \times 10^{-4} (3.4\sigma)$
  $\implies$ same as for 5 yr

- Blind search with 2yr data (6th and 7th yr):
  expected in the spot region $2.31$, observed $4$,
  $P = 0.2$
CORRELATION WITH LSS
Expected CR flux if sources trace LSS

protons, $E = 57$ EeV, $\theta = 6^\circ$, Galactic coordinates

C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); PI: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); Ursa Major North group (20 Mpc) South group (20 Mpc); V: Virgo cluster (20 Mpc).
7 yr events $E > 57$ EeV vs. LSS expectation

Equatorial coordinates. Darker color represents larger flux. **UM** — Ursa Major; **Co** — Coma; **V** — Virgo; **PP** — Perseus-Pisces
Statistical test for compatibility with LSS & isotropy

E > 57 EeV

Compatibility as a function of smearing angle $\theta$ (low p-values = incompatible).

- COMPATIBLE with LSS
- IN TENSION with isotropy
OTHER SEARCHES
Anisotropy in energy spectrum [method 1]

Strategy:

- Split the event set into “on-source” and “off-source” parts
- compare the “on-source” and “off-source” energy spectra

Two analyses:

- “On-source” = within 30° from Supergalactic plane
  \[\implies \sim 3.2\sigma\text{ difference (post-trial)}\]
- “On-source” = within 11° from VCV AGNs
  \[\implies \sim 2.4\sigma\text{ difference (post-trial)}\]
Anisotropy in energy spectrum [method 2]

Spectral differences “on” and “off” the hot-spot region
Anisotropy in energy spectrum [method 2]

- **Local**: 6.7\(\sigma\)
- **Global**: \(~4.0\sigma\)
Search for EeV protons of Galactic origin

Motivation:

- At the transition from ballistic to diffusive regime \((E \sim 1 \text{ EeV})\), one can predict the proton flux from galactic sources. It is strongly anisotropic.

- Comparing to observed flux, the proton component may be constrained.

Results:

- Fraction of Galactic protons in \(~1 \text{ EeV} UHECR\) is \(\lesssim 1\%\) at 90% CL.
COMBINED ANALYSES

- **Auger + TA**: Large-Scale Distribution of Arrival Directions of Cosmic Rays Detected at the Pierre Auger Observatory and the Telescope Array above $10^{19}$ eV
  
  > update on harmonic analysis of combined data set at $E > 10^{19}$ eV
  > non-zero dipole @ $2.8\sigma$

- **IceCube + Auger + TA**: Correlation between the UHECRs measured by the Pierre Auger Observatory and Telescope Array and neutrino candidate events from IceCube
  
  > highest energy $E > 57$ EeV Auger + TA events vs. neutrinos
  > correlation @ $3.4\sigma$
FIRST ALL-SKY UHECR FLUX MAP

Equatorial Coordinates - 60° smoothing

UHECR flux at $E > 10^{19} \text{ eV}$ (TA energy scale) in units of $\text{km}^{-2} \text{ yr}^{-1} \text{ sr}^{-1}$
FULL SKY AT GZK ENERGY?

Full sky map with nominal energies $E > 5.7 \times 10^{19}$ eV (potentially incorrect!)
ANISOTROPY SUMMARY

- Hints of anisotropy of UHECR start to appear:
  - dipole at low energies
  - “hot spot” in the GZK region
  - spectral variations over the sky

- WARNING: the significance is NOT yet sufficient for a definite conclusion
FUTURE
TA ×4 IS BEING BUILT!

- ×4 TA area (∼ 3000 km²)
- 500 scintillator SD; 2.08 km spacing
- 3 yrs construction (already started)
- 2 FD stations proposed to US NSF
- Get 19 TA-equiv years of SD data by 2020
- Get 16.3 TA-equiv years of hybrid data
SUMMARY

- **Spectrum:** measured over 4.7 orders of magnitude with a singly experiment
  - 4 features
  - Ankle and GZK break consistent with protons
- **Composition:** consistent with protons; also consistent with light mix
- **Anisotropy:**
  - no deviations from isotropy at low energies
  - a marginal anisotropy at $E > 57$ EeV (hot spot)
  - indication of spectrum variations over the sky
  - first all-sky map at $E > 10$ EeV (joint Auger-TA analysis)