Results from the Telescope Array Experiment

For the Telescope Array Collaboration

Charlie Jui

RICAP 2016, Frascati

June 22, 2016
5 nations, 33 institutions, 124 members
Outline

• Introduction to the Telescope Array (TA)
• Energy Spectrum
• Composition
• Anisotropy
• Future of TA
Telescope Array

507 scintillation counters surface detector (SD): Area: ~700 km².

3 fluorescence detector (FD) stations

In operation since 2008
Scintillation Counters

Pre-assembled in Japan, Final Assby/testing in Delta: 2 layers, 1.25 cm scintillator, 3m² area
Scintillator Detectors on a $1.2\ \text{km}$ square grid

- Power: Solar/Battery
- Readout: Radio
- Self-calibrated: $\mu$ background
- Operational: 3/2008
TA Fluorescence Detectors

Refurbished from HiRes-I
Observations since ~10/2007

New FDs
Observation since ~11/2007

Long Ridge
Observation since ~6/2007

Middle Drum
14 telescopes@station
256 PMTs/camera

Black Rock Mesa
Observation since ~6/2007

12 telescopes/station
256 PMTs/camera
Hamamatsu R9508
FOV~15x18deg

5.2 m²

1° pixels

6.8 m²

TA June 22, 2016
High Energy Hybrid Event

Energy: $1.3 \times 10^{20}$ eV
Zenith Angle: 55.7°

Surface array constrains geometry fit via extra timing & core information
1. Energy Spectrum

- Hybrid events

\[ E_{\text{ESSSS}} = E_{\text{ESSSS}} / 1.27 \]

- Energy Spectrum

- Angular resolution = 1.4°

- Energy resolution < 20%

- TA SD, \( \log_{10}(E/eV) \)

- (scaled to FD energy)

- \( E > 10^{19} \text{ eV} \)
**Piece-wise power-law fit**

- **Log(E/eV) ankle**: 
  \[ \log_{10}(E/eV) \text{ ankle} = 18.70 \pm 0.02 \]

- **Power index (ankle)**: 
  \[ \text{Power index} = -3.30 \pm 0.03 \]

- **Log(E/eV) GZK**: 
  \[ \log_{10}(E/eV) \text{ GZK} = 19.78 \pm 0.06 \]

- **Power index (GZK)**: 
  \[ \text{Power index} = -4.55 \pm 0.56 \]

**Previously Published:** 4 year TA surface detector spectrum

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 Telescopes installed and in operation since fall 2013
First 35 scintillation surface detectors deployed, 16 are instrumented and operational

64 more TALE SD (now funded in Japan) counters to be installed starting in September 2016
Nearby Events with Cerenkov

Azimuth [Degree]

Elevation [Degree]

Time, [$\mu$s]

2013/07/31 06:35:09.697828

23 21 19 18 16 17 15 12 24

23 21 19 18 16 17 15 12 24

23 21 19 18 16 17 15 12 24

23 21 19 18 16 17 15 12 24
Combined TA Energy Spectrum

Telescope Array Energy Spectrum: TALE + SD

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

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

$\gamma_1 = 3.19 \pm 0.01$

$\gamma_2 = 2.94 \pm 0.01$

$\gamma_3 = 3.22 \pm 0.01$

- TALE FD 1yr (PRELIMINARY)
- TA SD 7 year (ICRC 2015)
Combined TA Energy Spectrum

Telescope Array Energy Spectrum: TALE + SD

\[ \log_{10} E_{br} = 17.32 \pm 0.05 \]

\[ \log_{10} E_{br} = 16.20 \pm 0.02 \]

\[ \gamma_1 = 3.19 \pm 0.01 \]
Published Hybrid Composition (MD)

R. Abbasi et al. (TA Collab.)
Astropart Phys. (2014) 11 004

4 yrs, 297 Events $> 10^{18.4}$ eV
Cuts based on pattern recognition to improve resolutions $s \leq 25$ g/cm$^2$, all energies.
TA MD Hybrid Composition

Left: \(<X_{\text{max}}>\) vs \(\log(E)\) plot

Middle Drum Hybrid

- MD Hybrid Data
- Proton
- Nitrogen
- Iron

Update:
7 yr, 613 Events > \(10^{18.4}\) eV

Right: “Shift Plot”

Plot \(\Delta X_{\text{max}}\) required to maximize data/MC agreement (QGSJETII-03).
Standard statistical test on shifted distribution (points) Pink, blue bands for other hadronic models
16 g/cm\(^2\) systematic uncertainty
$X_{\text{MAX}}$ vs. $\log E$ for hybrid events from Black Rock and Long Ridge FD
$X_{\text{MAX}}$ vs. $\log E$
Stereo Events vs QGSJETII-03

Proton $X_{\text{max}}$ resolution, $E \geq 10^{19.4}$ eV

| Proton $X_{\text{max}}$ resolution, $E \geq 10^{19.4}$ eV |
|-----------------|---------|
| Entries         | 16242   |
| Mean            | -1.115  |
| RMS             | 21.81   |
| $\chi^2$/ndf   | 707.8/97|
| Constant        | 550.2±7.5|
| Mean            | -1.057±0.153|
| Sigma           | 18.98±0.16|

TA June 22, 2016
TA data compared to QGSJet-II.3

\[ \frac{(\text{data} - \text{iron})}{(\text{proton} - \text{iron})} \]

\[ \log(E(\text{eV})) \]

- MD Hybrid
- BR/LR Hybrid
- BR/LR/MD Stereo

\[ \ln A \]

\[ 0.0 \rightarrow p \]
\[ 1.0 \rightarrow \text{He} \]
\[ 2.0 \rightarrow \text{He} \]
\[ 3.0 \rightarrow \text{N} \]
\[ 4.0 \rightarrow \text{Fe} \]

Hypothetical Alternate Model
Meta-analysis: Auger-TA Composition Working Group

TA data cannot distinguish between mix and QGSJETII-03 protons at this level of systematic uncertainty.
TA Measurement of $\sigma_{p\text{-}\text{air}}$ (inelast.)

$\Lambda = 50.47 \pm 6.26$ [stat.] g/cm$^2$

$\sigma_{p\text{-}\text{air}}$(inelast.) = 567.0$\pm$70.5[Stat.] (+25,-29)[Sys.] mb

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Systematic (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Dependence</td>
<td>$\pm 17$</td>
</tr>
<tr>
<td>20%Helium</td>
<td>$+18$</td>
</tr>
<tr>
<td>Gamma&lt;1%*</td>
<td>$-23$</td>
</tr>
<tr>
<td>Total</td>
<td>(+25,-29)</td>
</tr>
</tbody>
</table>

R. Abbasi et. al. (TA collaboration)
Accepted for publication by Phys. Rev. D. Aug 2, 2015
Anisotropy Analysis: ICRC 2015

- SD data from period 12.05.2008 — 11.05.2015 (full 7 years)
- Zenith angle up to 55°, loose border cut
- Geometrical acceptance; exposure 8600 km² yr sr
- 2996 above 10 EeV
- 210 above 40 EeV
- 83 above 57 EeV
- Angular resolution: better than 1.5°
- Energy resolution: 20%
The TA Hot Spot

New 2-year data (37 events)
Total (2008 May 11 – 2015 May 11) 109 events

<table>
<thead>
<tr>
<th>Period</th>
<th>Total</th>
<th>Signal</th>
<th>B.G.</th>
<th>Chance Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-th Year</td>
<td>15</td>
<td>3</td>
<td>0.94</td>
<td>7%</td>
</tr>
<tr>
<td>7-th Year</td>
<td>22</td>
<td>1</td>
<td>1.37</td>
<td>74%</td>
</tr>
<tr>
<td>6th + 7th</td>
<td>37</td>
<td>4</td>
<td>2.31</td>
<td>20%</td>
</tr>
</tbody>
</table>

TA June 22, 2016
Max significance $5.1\sigma$ ($N_{\text{SIG}} = 24$, $N_{\text{BG}}=6.88$) for 7 years
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)
Global Excess Chance Probability: $3.7 \times 10^{-4}$ : $3.4\sigma$ (~same as first 5 years)
**Consistent with Fluctuation**

**K.S. Test** shows data is consistent with fluctuation for hotspot (Poisson: average = 3.43 per year, no time variation), but inconsistent with chance excess from isotropic distribution (Poisson: average = 0.9 per year) at ~ 2.6σ.
Energy Spectrum in the hot spot

MC normalized to spectrum outside hot spot region

**OutsideHotSpot**
- Entries: 805

**InsideHotSpot**
- Entries: 47

**Statistical Analysis**

- **Outside Hot Spot**
  - Entries: 13
  - $\chi^2 / ndf$: 6.727 / 9
  - Const: $0.883 \pm 0.380$
  - Slope: $0.005562 \pm 0.22458$

- **Inside Hot Spot**
  - Entries: 11
  - $\chi^2 / ndf$: 14.21 / 6
  - Const: $0.5824 \pm 0.9525$
  - Slope: $0.000162 \pm 0.81501$
Global Distributions

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

<table>
<thead>
<tr>
<th>Frame</th>
<th>Long.</th>
<th>Lat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>Supergalactic</td>
<td>0.01</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Autocorrelation

For each angular bin:

1. Count number of pairs of events at in the bin at separation $\delta$

2. Chance Probability is given by the fraction of isotropic MC sets (with equal statistics) with as many or more than the number of pairs seen in data

Compatible with isotropy at $E > 10$ EeV and $E > 40$ EeV, Tension with isotropy at $E > 57$ EeV
Correlation with Large-Scale Structure (LSS)

Gray patterns: expected flux density from proton (E>57 EeV)
LSS 2MASS Galaxy Redshift catalog (XSCz)

1D Kolmogorov-Smirnov p values comparing expected flux distribution (gray map from previous page) vs. simulation:
Marginally Incompatible with isotropic source simulation
Compatible with LSS source simulation

Cannot distinguish between LSS and isotropic simulations for E>10 EeV and E>40 EeV
**TA × 4 project**

**Quadruple TA SD (~3000 km²)**

- **500** scintillator SDs
- **2.08 km** spacing
- 2 additional FD stations

**Proposals**

- **SD: approved** in Japan
  - April 2015
- **FD: approved by NSF** in U.S
  - June 2016

**Collect 19 TA-equivalent years of SD data by 2020**

- Incl. 16.3 TA-equivalent years of hybrid data

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TA June 22, 2016
Summary

• TA has measured the energy spectrum, composition and arrival direction of UHE cosmic rays
• New TA Low Energy Extension (TALE) is coming on line. TALE surface detector array has now been funded by Gov’t of Japan.
• TA and TALE has measured energy spectrum between $6\times10^{15}$ eV to over $10^{20}$ eV and have observed spectral features
• The spectrum and composition of UHE cosmic rays measured by TA remain compatible with a single light component at above the ankle ($\sim6\times10^{18}$ eV).
• We have seen a hot spot in the direction of Ursa Major with 3.4$\sigma$ global significance
• Much more data are needed!
• TAx4 upgrade has been approved for funding both in Japan and in the U.S.
End
Reserve Slides
Analyzing SD Event

2008/Jun/25 - 19:45:52.58670 UTC

Geometry Fit (modified Linsley)

Fit with AGASA LDF

- S(800): Primary Energy
- Zenith attenuation by MC

Lateral Density Distribution Fit

\[ r = 800m \]
Surface Array Energy Measurement

- Energy table is constructed using the MC (CORSIKA)
- Determination of event energy by interpolating between S800 vs. sec(θ) lines
- Uses novel “de-thinning” of CORSIKA (paper draft in internal review)
Zenith Angle

LDF $\chi^2$/DOF

Pulse Height

Surface Detector Data-MC Comparisons

Surface Detector Exposure vs Log$_{10}E$

TA SD
2008/05/11-2015/05/11

6300 km$^2$ sr yr
Comparison of TA and Auger (+8.5% energy scale)
Energy Resolution and Exposure

Rel. Frequency vs. $\log_{10}(E/eV)$

- TA SD, $E > 10^{19.0}\,eV$, 18%
- TA BR/LR Mono, $10^{18.0} - 10^{18.5}\,eV$, 12%
- TALE Bridge, $10^{16.5} - 10^{18.5}\,eV$, 11%
- TALE Čerenkov, $10^{16.0}\,eV$, 16%

Exposure vs. $\log_{10}(E/eV)$

- TA SD 7 years
- TA BR/LR Mono, 7 years
- TALE Bridge 4 months
- TALE Čerenkov 4 months

CR17 EAS spec, Presented by Dmitri IVANOV on 4 Aug 2015 at 15:00
TALE Fluorescence Dominant Event

Shower Profile

$\chi^2 / \text{ndf}$: 120.65 / 65

$\log_{10}(E)$: 17.88

$X_{\text{Max}}$: 752.86

$N_{\text{Max}}$: 4.87e+08
Fitting the UHE Spectrum with TA

Fitting parameters:

- Power law at the source, $E^{-p}$
- Evolution of the sources, $(1+z)^m$

$p = 2.18^{+0.08}_{-0.14}$, $m = 6.8^{+1.6}_{-1.1}$ (stat. + sys.)
TALE Cherenkov Dominant Event

Shower Profile
\[ \chi^2 / \text{ndf} \] 62.80 / 46
\[ \log_{10}(E) \] 17.50
\[ X_{\text{Max}} \] 538.55
\[ N_{\text{Max}} \] 2.16e+08

Time vs Angle, TALE-FD-Mono
\[ \chi^2 / \text{ndf} \] 5.867 / 46
\[ T_0 \] -1.353 ± 2.597
\[ R_p \] 2461 ± 483.8
\[ \Psi \] 78.79 ± 39.24
Composition: Xmax Technique

- Shower longitudinal development depends on primary particle type.
- FD observes shower development directly.
- Xmax is the most efficient parameter for determining primary particle type.

**Shower longitudinal development**

![Graph showing number of charged particles vs. depth](image)

**HiRes**

*PRL.104.161101 (2010)*

**Auger**

*PRL.104.091101 (2010)*
Latest TA Hybrid Composition Analysis

• 5 Years MD FD+SD hybrid data
• Geometrical Event Selection Criteria:
  – Geometry fit $\chi^2$/dof < 4.5
  – $\log_{10} E($eV$) > 18.2$
  – Hybrid core < 1600m from SD core
  – Hybrid Core inside SD array or < 500m outside
  – Zenith angle < 58°
  – Xmax within view (20g/cm$^2$ at start, and 0g/cm$^2$ at end)

New: Patter recognition test on shower profile
Failed: large triangle obliqueness test

Quartic polynomial (weight squared) fit used to determine the apex of the large triangle

Passed: highest energy MD hybrid event
Hybrid $X_{\text{max}}$ Measurement

Xmax Data comparison to QGSjet II-03 *proton* and *iron* models
Astrophysically p and He are very different

Interaction lengths of p, He, O and Fe
<Xmax> Uncertainty from Extrapolation of Cosmic Ray Air Shower Parameters

Study the effect on the <Xmax> of HE Model using CONEX4.44 at $10^{19.5}$ eV

Gordon Thomson & R. Abbasi U12
**Photon Limits**

Photon-induced showers: arrive younger contain fewer muons
⇒ multiple SD observables affected:
Front curvature, Area-over-peak, # of FADC signal peaks, χ²/d.o.f.

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**TA Surface Detector**

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**TA Hybrid**

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TA June 22, 2016
No correction for Energy scale difference b/w TA and PAO !!

TA : 7 years 109 events (>57EeV)
PAO : 10 years 157 events (>57EeV)

Oversampling with 20°-radius circle
Southern hotspot is seen at Cen A(Pre-trial ~3.6σ)
Nearby Prominent Sources

The blazar Mrk421, Mrk180 and starburst galaxy M82 are candidates?

Nearby Galaxy Clusters

- Ursa Major Cluster (D=20Mpc)
- Virgo Cluster (D=20Mpc)
- Perseus-Pisces Supercluster (D=70Mpc)
- Eridanus Cluster (D=30Mpc)
- Fornax Cluster
- Centaurus Supercluster (D=60Mpc)

Dots: 2MASS catalog Heliocentric velocity <3000 km/s (D<~45Mpc)


TA hotspot is found near the Ursa Major Cluster. TA & PAO found no excess in the direction of Virgo.
Energy Spectrum in the hot spot

$E^3 \times \text{Differential Flux}$

$J(E) \times E^3 / 10^{24} \left[ \text{m}^{-2} \times \text{s}^{-1} \times \text{sr}^{-1} \times \text{eV}^2 \right]$

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

$J_1 / J_2$

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

PRELIMINARY JUNE 2016
Observed cosmic ray energy spectra are compared between sky areas that have larger density of nearby objects, such as the super-galactic plane, and others that do not. The distributions differ. We found the chance probability to obtain the difference in statistically equivalent distributions is estimated as $6.2 \times 10^{-4}$ (3.2σ).
... observed energy distributions of events within 11° from VCV AGNs and out of this region were compared. Chance probability to obtain observed difference in statistically equivalent distributions is estimated as $1.5 \times 10^{-2}$ after considering penalty factor.
Comparison with Large-Scale Structure (LSS)

E > 10 EeV: 2130 events

E > 40 EeV: 132 events

E > 57 EeV: 52 events

White dots: 5-year TA data with zenith angle < 55 deg.

Gray patterns: expected flux density from proton LSS 2MASS Galaxy Redshift catalog (XSCz)
The trajectory of the EAS can be determined in one of two ways:

1. Monocular reconstruction using the arrival time of light signal at the detector.
2. By intersecting the shower-detector planes (SDP) seen from the two detector sites.