Обзор результатов Обсерватории Telescope Array

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от имени коллаборации Telescope Array

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Outline

• Telescope Array observatory and TAx4 upgrade
• Energy Spectrum results
• Composition and hadronic interactions results
• Anisotropy results
• Interdisciplinary results
• Summary
Telescope Array Collaboration


1 Loyola University Chicago2 University of Utah3 Saltama University4 Osaka City University5 Hanyang University6 Tokyo University of Science7 University of Tokyo (ICRR)8 Kyoto University9 Shinshu University10 Kanagawa University11 University of Yamanashi12 Shinshu University (Inst. of Engineering)13 RIKEN14 Sungkyunkwan University15 Tokyo City University16 Institute for Nuclear Research of the Russian Academy of Sciences17 Shibaura Institute of Technology18 Osaka Electro-Communication University19 Chiba University20 Université Libre de Bruxelles21 Yonsei University22 University of Nova Gorica23 Kochi University24 Osaka City University (Nambu Yoichiro Institute)25 Ritsumeikan University26 Osaka Inst. for Information and Communications Technology, Tokyo27 Lomonosov Moscow State University28 Ulsan National Institute of Science and Technology29 University of Tokyo (Earthquake Inst.)30 Hiroshima City University31 KEK32 Tokyo University of Science33 National Inst. for Quantum and Radiological Science and Technology34 CEICO, Institute of Physics

160 members, 35 institutes, 7 countries
Telescope Array: The largest cosmic ray observatory in the Northern Hemisphere

Telescope Array
Delta, Utah, USA. ~1400 m a.s. l.
Collaborators from HiRes, AGASA and other institutes

Science goals:
• Origin and properties of the ultra-high energy cosmic rays:
  • spectrum, composition, anisotropy
  • Physics of HE hadronic interactions
  • Multi-messenger and interdisciplinary studies
    • photons, neutrino, dark matter
    • thunderstorms, TGFs
    • meteoroids
• Development of the next generation experiments
Map of the TA site

Fluorescence Detectors (FDs)
- Middle Drum (MD): 14 telescopes
- TA Low energy Extension (TALE): 10 FDs

Surface detectors (SDs)
- 507 scintillation detectors
- 2 layers, 3m² each
- 1.2km spacing
- total coverage ~700km²

Central Laser Facility

FDs
- Long Ridge (LR) station: 12 telescopes
- Black Rock Mesa (BRM) station: 12 telescopes

Telescope Array Locations
General Reference Map

3 communication towers
For the SD array

Border of FD station FOV
20km
TALE

Located in TA MD site
10 FDs in the TALE station
Elevation: 30°-57° (higher elevation than MD) Azimuthal: 114°

104 SD infill array identical to main TA SD
Variable spacing up to 400m

TALE FD Installed in Nov. 2012
Operation since Sep. 2013

TALE SD completed Mar. 2018
Hybrid trigger: Sep. 2018

Zatsepin Readings 2022
Goal: fourfold increase in size of TA SD array (up to 3000 km$^2$).
Triple statistics for E>20 EeV in 5 years.

Hybrid experiment:
- 2 FD stations, 12 telescopes are installed
- 257 SD scintillators out of 500 are installed and operational since Nov. 2019
SD Event Reconstruction

Event map:
- Size = # of particles
- Color = timing

Time fit

Modified empirical formula in AGASA

Lateral distribution profile fit

Empirical formula used by AGASA

Zatsepin Readings 2022
Event reconstruction

Stereo
Line intersection of shower detector planes

Hybrid

Stereoscopic Detector Plane

Comparing with MC -> $X_{\text{max}}$
Integration of signals -> 1st try $E$

Reconstructed shower profiles

Observed images
TAx4 Hybrid Event Example
Energy spectrum
TA SD Energy Spectrum

Fit to broken power law

Power index
-3.28 ± 0.02

Power index
-2.68 ± 0.02

Power index
-4.84 ± 0.48

Log (E (eV)) Ankle
18.69 ± 0.01

Log (E (eV)) E₂
19.81 ± 0.03

TA SD 11 years data

TAX4 SD 1 year data

Preliminary

Zatsepin Readings 2022
Combined Energy Spectrum

- Knee: \( E_K \) = 16.22 ± 0.02
- Second knee: \( E_K \) = 17.04 ± 0.04
- Ankle: \( E_K \) = 18.69 ± 0.01
- Cutoff: \( E_K \) = 19.81 ± 0.03

Combined TA spectrum using 22 months TALE FD monocular data + 11 years TA SD data
The “Instep” feature

Pierre Auger found a spectrum softening in $10^{19} - 10^{19.5}$ eV range. Combining TA SD, FD and HiRes data, we observe the Instep feature in the Northern Hemisphere at $10^{19.25\pm0.03}$ eV with a 5.3 $\sigma$ significance.

Dmitry Ivanov, ICRC’2021

Yoshiki Tsunesada, Auger+TA spectrum WG, ICRC’2021
Joint Auger + TA spectrum WG result

Absolute energy scale difference 9% + energy-dependent shift of ±10% per decade

Yoshiki Tsunesada, ICRC'2021
Chemical composition and hadronic interactions
A break in the elongation rate at energy $10^{17.2} \text{ eV}$

Tareq AbuZayyad, ICRC’2021

TALE FD monocular XMAX

TA and TALE hybrid XMAX

TALE hybrid

Elongation plot: $<X_{\text{max}}>$

- $X_{\text{max}}$ [g/cm$^2$]
- $\log E$ [eV]

- TA Preliminary
- 12-23 July 2021
- Keitaro Fujita, ICRC’2021

TA hybrid

- 4y Preliminary
- Heungsu Shin, ICRC’2021

- break point: 17.07 ± 0.09
- before slope: 25.78 ± 14.52
- after slope: 95.13 ± 10.99
- $\chi^2$/ndf: 0.34 ($p = 0.98$)

- qgs04 proton, rec.
- qgs04 iron, rec.
- xmax Broken Line Fit
TA SD composition

Machine learning technique based on BDT and 16 composition-sensitive observables with 12 years of TA SD data

Yana Zhezher, ICRC’2021
TASD UHE photon limits

New p-γ classifier based on neural network. Classifier uses full time-resolved signals from all triggered SD stations along with 16 composition-sensitive observables.

Oleg Kalashev, Ivan Kharuk, GR, ICRC’2021
TA proton-air cross-section

Measuring XMAX attenuation length in hybrid mode.

TA Collaboration, Phys. Rev. D 102, 062004
Anisotropy
CR clustering: Dipole update (12-yr)

Sky map of residual intensity between TA data and an isotropic distribution for $E > 8.8$ EeV (energy cut corresponds to $E > 8$ EeV used by Auger).

TA 12-yr result: $r_\alpha \approx 3.1\%$; $\phi_\alpha \approx 134^\circ$

Auger 2017 result: $r_\alpha \approx 4.7\%$; $\phi_\alpha \approx 100^\circ$

Toshihiro Fujii, ICRC’2021
**CR clustering: Hot spot update (12-yr)**

First 5-yrs: 72 events  
S at hotspot center = $5\sigma$

Last 7-yrs: 107 events  
S at hotspot center = $2.3\sigma$

Energy E > 57 EeV

Overall post-trial significance has dropped from $3.4\sigma$ to $3.2\sigma$

The growth rate of events inside the hotspot is consistent with the linear one within $\sim 1\sigma$

Jihyun Kim, ICRC’2021
CR clustering: Medium scales

Hint of excess in the direction of Perseus-Pisces supercluster

TA Collaboration, arXiv:2110.14827
Correlation with LSS: chemical composition

Upper limits on proton and iron fractions at 68% C.L. as functions of energy, derived from correlation with LSS

Mikhail Kuznetsov, ICRC’2021

Sky map $\Phi_k$ of expected flux from LSS at $E_k = 57$ EeV.
Declination Dependence of Spectrum

- Difference of the cutoff energies of energy spectra
  - $\log(E/eV) = 19.64 \pm 0.04$ for lower dec. band (-16° - 24.8°)
  - $\log(E/eV) = 19.84 \pm 0.02$ for higher dec. band (24.8° - 90°)
- The global significance of the difference is estimated to be $4.3\sigma$
Interdisciplinary results
Observation of Terrestrial Gamma-Ray Flashes with T ASD

- Broadband Interferometer (INTF):
  - Three 20-80 MHz flatplate antennas
  - 2D high-resolution reconstruction of lightning sources
- Fast Sferic Sensor (FA):
  - Detects electric field change
  - Identifies substructure: initial breakdown pulses (IBPs)
- Clearly defined TGF onset during the flash’s strongest initial breakdown pulse

TA Collaboration, arXiv:2205.05115
Variation of Level-0 trigger rate during Thunderstorms

- Level-0 trigger rate is monitored at 10 min resolution at each SD station.
- Thunderstorm detected by NLDN changes the trigger rate.
- The result may be interpreted by using EFIELD option of CORSIKA.
- Intensity increase or deficit depends on electric field type (intracloud or cloud to ground) and thunderstorm polarity.

TA Collaboration, Phys. Rev. D 105, 062002
Extension of TALE SD: TALE-infill

Shoichi Ogio, ICRC’2021
Summary

• Telescope Array is UHECR Observatory in the Northern Hemisphere
• Energy spectrum is measured from $10^{15.5}$ to $10^{20.5}$ eV (5 decades)
  • New feature in the energy spectrum at $\sim 10^{19.3}$eV
  • TA Low Energy Extension (TALE) energy spectrum indicated that second knee may result from Peters cycle ($10^{15.6}$eV → $10^{17.1}$eV)
• TALE Xmax shows composition becoming heavier between first and second knee, consistent with Peters Cycle interpretation
• Between $10^{18.0}$ eV and $10^{19.1}$eV TA hybrid data is compatible with predominantly light elements such as protons and helium
• Indications of anisotropy at highest energy
  • Hot spot from 12 years of data in the direction of Ursa Major (3.2 $\sigma$ post trial)
  • Hint of excess in the direction of Perseus Pisces E > $10^{19.3}$eV
  • Correlation with LSS consistent with large fraction of protons
  • Declination dependence of the spectrum
• We need much more data at high energy end → TAx4 in operation!