Cosmic Rays from $10^{16} - 10^{21}$ eV

John Matthews

University of Utah
High Energy Astrophysics Institute
Department of Physics and Astronomy

Photo: Ben Stokes, U of Utah

BNO-50 Kabardino-Balkarian State University, Nalchik, Russia 8 June 2017
Cosmic Ray Flux

- Extends over a wide energy range
- Almost featureless
  - Slope \( \sim (-3) \)
  - Slight “knee” at \( 3 \times 10^{15} \) eV
- Flux is \( \sim \) isotropic due to galactic magnetic fields.
- Direct Measurements \( \sim E < 10^{15} \) eV
- Above this indirect measurements
J.N. Matthews
Baksan Neutrino Observatory BNO-50

GZK-Cutoff

$\gamma_{2.7K} \rightarrow ^{12}(1232)$
$-p + \nu^0 \rightarrow p\gamma\gamma$
$-n + \nu^+ \rightarrow pe^+\nu$

$\gamma_{3K} (400 \text{ cm}^{-3})$

Lake Baikal, August 2016

Andreas Haungs for the Pierre Auger Collaboration
 Cosmic Rays at highest energies in 2003

Source, acceleration, and mass of the particles unknown – but they exist!
Exists the cut-off? (strong extragalactic processes which happens very close are necessary)

Measurements by
large particle detector arrays (AGASA - no cutoff)
or
fluorescence telescopes (HiRes cutoff (observed 11
events while expecting 30, if no cut-off 7x10⁻⁵ probability)

Spectrum before Auger

Cutoff yes or no?
First interaction (usually several 10 km high)

Air shower evolves (particles are created and most of them later stop or decay)

Measurement of Cherenkov light with telescopes or wide angle pmts

Some of the particles reach the ground

Measurement with scintillation counters

Measurement of radio emission

Measurement of fluorescence light

Measurement of particles with tracking detectors or calorimeters

Measurement of low energy muons with scintillation or tracking detectors

Measurement of high energy muons deep underground
Telescope Array

700 km²: Lat. 39.30°N, Long. 112.91°W  1550m ASL
The High Energy component of Telescope Array – 38 fluorescence telescopes (9728 PMTs) at 3 telescope stations overlooking an array of 507 scintillator surface detectors (SD) - complete and operational as of ~1/2008.
Telescope Array: Operational 3/2008

Middle Drum

14 telescopes @ station
256 PMTs/camera

Reutilized from HiRes-I

Long Ridge

Black Rock Mesa

New Telescopes

~30km

5.2 m²

12 telescopes/station
256 PMTs/camera

~1 m²

6.8 m²
Photo: Oleg Kalachev, INR RAS
Typical Fluorescence Event

Event Display
Black Rock Mesa

Monocular timing fit (time vs angle)

Reconstructed Shower Profile

Fluorescence
Direct (Cerenkov)
Rayleigh scatt.
Aerosol scatt.
Scintillator Surface Detectors

2 layers scintillator
1.25 cm thick, 3m² area
Optical fibers to PMTs
Scintillator Detectors on a 1.2 km square grid

- Power: Solar/Battery
- Readout: Radio
- Self-calibrated: $\mu$ background
- Operational: 3/2008
TA shower analysis with SD

An SD hit map of a typical high energy event
Example Event

<table>
<thead>
<tr>
<th></th>
<th>$\theta$ [°]</th>
<th>$\phi$ [°]</th>
<th>x[km]</th>
<th>y[km]</th>
</tr>
</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>

Event from 2008-10-26
Pierre Auger Observatory: completed 7/2008

Area: 3000 km²
1600 surface detector stations: water-Cherenkov tanks (triangular grid of 1.5 km)
4 fluorescence detectors (24 telescopes in total)
2 laser stations
balloon station

~25 km² infill area
HEAT, AMIGA, AERA

Andreas Haungs for the Pierre Auger Collaboration
FD: six telescopes each viewing 30° by 30°
Surface detector array in the Argentinean Pampa

Lake Baikal, August 2016

Andreas Haungs for the Pierre Auger Collaboration
Energy Scale Check and Resolution

(SD scaled to FD energy: calorimetric)

\[ E_{SD}/1.27 = E_{FD} \]

- **Entries**: 551
- **Angular resolution**: 1.4°
- **Energy resolution**: < 20%

8 June 2017 J.N. Matthews BNO-50
Energy Spectrum
Energy Spectrum

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5} J(E)$ (m$^{-2}$ s$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

<20% energy scale uncertainty
TA SD Spectrum (7 yrs data)

Piece-wise power-law fit

- Power index
  - Log(E/eV) ankle: $18.70 \pm 0.02$
  - Power index: $-2.68 \pm 0.03$
  - Log(E/eV) GZK: $19.78 \pm 0.06$
  - Power index: $-4.55 \pm 0.56$

- N_EXPECT (> GZK, no cut-off): 99.332
- N_OBSERVE (data > GZK): 44
- GZK CHANCE PROBABILITY: $4 \times 10^{-10} \sim 6\sigma$
- BEREZINSKY E_{1/2, log10(E/eV)}: $19.77 \pm 0.06$

Previously Published: 4 year TA surface detector spectrum
Comparison of TA and Auger (+8.5%) Spectra
TA Low Energy Extension (TALE)
Galactic to Extra-Galactic Transition

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

Graded infill surface detector array - more densely packed surface detectors (lower energy threshold)
All 10 Telescopes installed and in operation since fall 2013
Test array of 16 scintillation surface detectors in operation
**TALE SD infill array recently funded from Japan – deploy to field 2016-17**
Nearby Events with Cerenkov
Comparison with other Measurements

![Graph showing comparison with other measurements](image)

- HiRes-II (2008)
- Yakutsk Cherenkov (2013)
- Tunka-55 (2013)
- Tunka-133 (2013)
- KASCADE-Grande (2011)
- Auger (2013)
- ICETOP (2013)
- TA Combined (ICRC 2015)
TALE/NICHE Low Energy

103 TALE SDs
installed 2/2017
Commissioning
6-7/2017

NICHE (15) Cerenkov detector
array under installation
between TALE array and
northern Telescope Station
UHECR Composition

- Use hybrid or stereo to constrain geometry and know $X_{\text{max}}$
- Stereo also provides a redundant measurement of $X_{\text{max}}$
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
Stereo Observation

Intersect shower planes to get more precise geometry
**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:

![Diagram showing shower longitudinal development with Xmax marked](image)

**PRL.104.161101 (2010)**

**HiRes**

**PRL.104.091101 (2010)**

**Auger**
Hybrid Observation

  4 yrs, 297 Events > $10^{18.4}$ eV
- Cuts based on pattern recognition technique to improve resolutions $s \leq 25 \text{ g/cm}^2$, all energies.
- Update:
  7 yr, 613 Events > $10^{18.4}$ eV
Hybrid $X_{\text{max}}$ Measurement

Xmax Data comparison to QGSjet II-03 proton and iron models
MD Hybrid

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

```
<table>
<thead>
<tr>
<th>Systematic Error</th>
<th>MD Hybrid Data</th>
<th>Proton</th>
<th>Nitrogen</th>
<th>Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>16 g/cm²</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

“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/cm² systematic uncertainty
TA data compared to QGSJet-II.3
Astrophysically p and He are very different

Interaction lengths of p, He, O and Fe
Auger Composition: mean depth and rms of shower maximum

Composition is getting heavier with energy
Method only applicable up to 50EeV due to statistics
Photon/Neutrino Searches

• See Presentation by G. Rubtsov, INR
Anisotropy
Published Hotspot (5yr data)

$E > 5.7 \times 10^{19}$ eV (72 events)

Aitoff projection in Equatorial Coordinates

Events over-sampled using 20° circles

19/72 events fall in hotspot $\sim (146.7°, 43.2°)$

4.5 events expected (26% of events in 6% of the area)

LiMa significance: $5.2\sigma$  
Estimate $3.4\sigma$  
chance probability
Nearby Galaxy Clusters

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

TA hotspot is found near the Ursa Major Cluster
TA & PAO see no excess in the direction of Virgo.
New 2-year data (37 events)
Total (2008 May 11 – 2015 May 11) 109 events
Max significance $5.1\sigma$ ($N_{SIG} = 24$, $N_{BG} = 6.88$) for 7 years
Global Excess Chance Probability: $3.7 \times 10^{-4}$: $3.4\sigma$ (~ same as first 5 years)
The Future:
**TA × 4 Project**

**Quadruple** TA SD (~3000 km²)

- **500** scintillator SDs
- **2.08 km** spacing
  
  Approved in Japan 2015
  
  3 yrs construction, first 100 SDs have arrived in Utah (2016-05)

2 FD stations (12 HiRes Telescopes)

Funding approved US summer 2016

**Get 19 TA-equiv years of SD data by 2020**

Get 16.3 (current) TA years of hybrid data
Clarify the details of the Hotspot
Simulated 19 TA-equiv yrs data

Single Source

Two Separated Sources
Auger Prime Upgrade

- Engineering array in Argentina
- Construction 01/2017 - 2018
- Costs: 12.5 M€ >70% already committed
- Data taking into 2025
EUSO / POEMMA

• JEM – EUSO
• KLEPVE – EUSO (MSU)
• EUSO – Balloon (CNES; Canada, Aug 2014, 5 hr)
• EUSO – SPB (CSOM; Apr-May, 2017)
• Mini – EUSO (MSU, RusCosmos; Fall, 2017?)
• ....
• POEMMA?
EUSO-TA

2013: Installation, building, lenses
2014: for Auger/FAST tests
2015:
  • Detector installation
  • FOV +/- 8°
  • Initial CLF and CSOM laser observations
  • Cosmic ray observations – UHECRs detected
  • Internal trigger tests on the balloon PDM board
2016: Tests in conjunction with EUSO-SPB1

Photon Detection Module
48x48=2304 pixels
Single Photoelectron Counting
2.5 µS time bins
1 “video clip” = 128 bins = 320 µS
~15 watts
EUSO – SPB1

Telemetry for Commands and Data
Tracker Beacon for aircraft underflight
Exoskeleton
Ballast Hopper 1 of 2

EUSO-SPB Payload and Major Components
- CSBF SIP
- Electronics Compartment + PDM, CPU, Batteries
- Lens Box
- UCIRC IR Camera

EUSO-SPB Specs

- SPB Float Height: 110,000 ft = 33.5 km
- Weight:
  - Detector: 2250 lbs
  - Payload: 2700 lbs w/ SIP, Antennas, Empty Ballast Hoppers
- Dimensions: 1.2m x 1.2m x 3m
- Power consumption: 40 W Day, 70 W Night (assumes 20W PDM heater @ 50%)
- Telescope: Refractor with 2 Fresnel lenses
- FOV: 11° deg (measured w/ stars)
- Camera: 2.304 pixels; 36 MAPMTS (Hamamatsu R11265-113-M64-MOD2)
- Data volume: Downlinked ~1-1.5 Gb/day
- Recorded: ~3 GB/Day w/ 10 hour dark run with trigger rate of 0.2 Hz
- Energy threshold: for h=33 km ~3 EeV
- Ground equivalent Trigger Aperture: 250 km^2 sr @ 3 EeV to ~500 km^2 sr @ 10 EeV

Leak -> Termination
Conclusions 1

• UHECR Flux suppression verified by Telescope Array and Pierre Auger
• Telescope Array consistent with GZK cutoff, Auger spectrum cuts off a bit lower energy
• Telescope Array energy range being expanded below $10^{16}$ eV with TALE – Spectral shape looks consistent with Yakutsk Cerenkov, Tunka-133, Kascade-Grande, and Ice Top – Normalization in progress
• Telescope Array observes four spectral features over >5 orders of magnitude in energy with one cross-calibrated set of detectors
Conclusions 2

• $10^{17} - 10^{18}$ eV composition goes heavy to light
• $>10^{19.3}$
  – Telescope Array light (protonic) composition
  – Auger composition getting significantly heavier

• $E > 5.7x10^{19}$ Telescope Array observes indications ($3.4\sigma$) of medium scale anisotropy

• TAx4 -> expansion to $\sim$ aperture of Auger
• Auger Prime – add Scintillators
• EUSO broad program moving forward
Summary

• TA has measured the energy spectrum, composition and arrival direction of UHE cosmic rays
• The spectrum and composition of UHE cosmic rays measured by TA remain compatible with a single light component at above the ankle ($\sim 6 \times 10^{18} \text{ eV}$).
• We have reported a hot spot seen in the direction of Ursa Major with $3.4\sigma$ significance
• **New:** TA Low Energy Extension (TALE) is coming on line. TALE surface detector array was funded by the Univ. of Utah and was recently been funded by Gov’t of Japan.
• TA and TALE have measured energy spectrum between $6 \times 10^{15} \text{ eV}$ to over $10^{20} \text{ eV}$ with a single cross-calibrated set of detectors and have observed spectral features
• **Much more data are needed! – coming soon TAx4**
Galactic to Extra-Galactic Transition

- Previous suspected structure
- Unknown energy scale
- Tie down the energy scale and simultaneously measure spectrum and composition
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.)
Test Correlations with AGNs

- 472 AGN from 2006 Veron catalog with $z < 0.018$
- $E > 57$ EeV, zenith angle $< 45^\circ$, $N = 42$ (5 yr)
- Separation angle $= 3.1^\circ$
Correlations with AGNs

Probability of event overlapping with AGN is $p_o = 0.24$
Find 17 events correlate of 42 $\Rightarrow$ $p = 0.014$