Interpretation of the energy spectrum observed with the Telescope Array surface detectors

E. Kido and O.E. Kalashev
for the Telescope Array Collaboration
Outline

• Introduction
• Data set of TA SD energy spectrum
• Assumptions and conditions of the model calculations
• Fit 7 years TA SD energy spectrum with the model
  – On systematic uncertainty of model calculations
    • Propagation codes (TransportCR/CRPropa)
    • Source distribution (uniform/LSS)
    • IRB models
  – Constraint on distance to the closest source
• Summary and conclusions
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5 countries, ~120 collaborators
Utah, USA
- lat. 39.30°N, long. 112.91°W

1.2 km spacing ~ 700 km²
507 SDs

12 telescopes

Surface Detector (SD)

Fluorescence Detector (FD) station

TALE SD array

FD station

MDFD

28 km

LRFD

BRFD

SD array
Introduction

Telescope Array (TA) SD observed energy spectrum \((E > 10^{18.2}\ eV)\) with high statistics


Ankle \((10^{18.70\pm0.02}\ eV)\) and break \((10^{19.78\pm0.06}\ eV)\) obtained from broken power law fit: consistent with the expectation pure proton model (“dip” model) from extragalactic sources

\(\text{Ankle} \approx 10^{18.7\ eV}\ \text{break} = 10^{19.72\ eV}\)

Berezinsky and Gregor’eva (1988)
Berezinsky et al. (2006)

→ Test pure proton model using TA SD energy spectrum in more detail
Data set

- 7 years: May 11 2008 – May 11 2015
- Zenith angle < 45 (deg.)
- $E > 10^{18.2}$ eV, 20692 events
- Energy resolution:

![Histograms showing energy resolution for different energy ranges.](Image)
• Pure proton, $E > 10^{18.2} \text{ eV}$

• Injection spectrum $E^{-p}$, $E_{\text{max}} = 10^{21} \text{ eV}$

• Source density $\propto (1 + z)^m$ (per comoving unit volume)
  LSS source distribution ($z < \sim 0.06$) is also considered (next slide)

• Energy losses with CMB and IRB ("best-fit model" T.M. Kneiske et al., Astron. Astrophys. 413, 807 (2004)) are considered.


• Propagation without considering magnetic fields
  $\rightarrow Z < \sim 0.7$, $B_{\text{IGMF}} < \sim 0.1 \text{ nG}$
LSS source distribution

- Number density of 2 Mass XSCz catalog $\sim 110,000$ galaxies is used.
- $5 \text{ Mpc} < D < 250 \text{ Mpc}$
- Ks magnitude $< 12.5$
- Weights are considered for the limit of the apparent magnitude.
- TA exposure is considered for each direction of the galaxy.
Procedure of fitting energy spectrum

Maximum likelihood with binned data

Estimator:

\[-2 \ln \lambda(\theta) = 2 \sum_{i=1}^{N} \left[ \mu_i(\theta) - n_i + n_i \ln \frac{n_i}{\mu_i(\theta)} \right]\]

\(n_i\): number of events in i-th energy bin

\(\mu_i\): expected number of events in i-th energy bin

\(\Theta\): 4 fit parameters

\(E^p, (1 + z)^m, \Delta \log_{10} E, \) normalization of \(\mu_i\)

\(\Delta \log E = \log E - \log E_{\text{obs}}\) : energy shift of the data

Particle Data Group
review of statistics (2014)
Section 38.2.2.1
Best fit model energy spectrum with 7 years TA SD energy spectrum

Uniform: best fit $\chi^2(-2\ln L)/\text{d.o.f.} = 27.6/17$
LSS: best fit $\chi^2(-2\ln L)/\text{d.o.f.} = 24.5/17$
Above $10^{18.2}$ eV
With only statistical errors

Best fit values: listed below

<table>
<thead>
<tr>
<th></th>
<th>uniform</th>
<th>LSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>2.15</td>
<td>2.17</td>
</tr>
<tr>
<td>$m$</td>
<td>6.9</td>
<td>7.2</td>
</tr>
<tr>
<td>$\Delta \log_{10} E$</td>
<td>-0.06 (-13%)</td>
<td>-0.04 (-9%)</td>
</tr>
<tr>
<td>Normalization</td>
<td>arbitrary</td>
<td>arbitrary</td>
</tr>
</tbody>
</table>

$\Delta \log E = \log E - \log E_{\text{obs}}$ : energy shift of the data

$E > 10^{18.2}$ eV
$\Leftrightarrow Z < \sim 0.7$

4-parameter fit
Best fit model energy spectrum with 7 years TA SD energy spectrum

$E > 10^{18.2} \text{ eV}$
$\Leftrightarrow Z < \sim 0.7$

4-parameter fit

Best fit values: listed below

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<thead>
<tr>
<th>Parameter</th>
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</tbody>
</table>

Normalization arbitrary arbitrary

$\Delta \log E = \log E - \log E_{\text{obs}}$ : energy shift of the data
Best fit model energy spectrum with 7 years TA SD energy spectrum

$\sigma_{\text{SYS}} \sim 3\%$ of the flux for all energies. Mainly from the calculation of the acceptance $\sigma_{\text{TOT}} = \sqrt{\sigma_{\text{STAT}}^2 + \sigma_{\text{SYS}}^2}$: Gaussian distribution

<table>
<thead>
<tr>
<th>Uniform:</th>
<th>$\chi^2/\text{d.o.f.} = 18.0/17$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic error of the flux is also considered.</td>
<td>Data is compatible with pure proton model</td>
</tr>
</tbody>
</table>

\[ \Delta \log_{10} E = -0.04 \quad (-9\%) \]

Normalization: arbitrary

\[ \Delta \log E = \log E - \log E_{\text{obs}} \]

<table>
<thead>
<tr>
<th>Uniform</th>
<th>$p$</th>
<th>2.18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m$</td>
<td>6.8</td>
</tr>
</tbody>
</table>

2014/10/13
Conclusive determined fitting parameters

\[ (1 + z)^m \]

<table>
<thead>
<tr>
<th>( p )</th>
<th>( m )</th>
<th>( \Delta \log_{10} E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.97</td>
<td>-0.35</td>
</tr>
<tr>
<td>-0.97</td>
<td>1</td>
<td>0.53</td>
</tr>
<tr>
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<td>0.53</td>
<td>1</td>
</tr>
</tbody>
</table>

Correlation coefficient

Chi\(^2\) min./d.o.f. = 18.0/17

\[ p = 2.18 - 0.14 + 0.08 \text{ (stat.+sys.)} \]
\[ m = 6.8 - 1.1 + 1.6 \]
\[ \Delta \log_{10} E = -0.04 (-9\%) - 0.03 + 0.04 \]
Systematic uncertainty of model calculations

- Propagation codes
  - Difference of best fit parameters:
    \[ \Delta p = 0.01, \Delta m = 0.1, \Delta (\Delta \log_{10} E) = 0.01 \]

- Uniform/LSS source distribution
  - Difference of best fit parameters:
    \[ \Delta p = 0.02, \Delta m = 0.3, \Delta (\Delta \log_{10} E) = 0.02 \]

- IRB models
  - Difference of best fit parameters:
    \[ \Delta p = 0.04, \Delta m = 0.3, \Delta (\Delta \log_{10} E) = 0.01 \]

These uncertainties are much smaller than the uncertainties of data.
Fit energy spectrum at highest energy with parameter $Z_{\text{min}}$ (No sources $Z < Z_{\text{min}}$) → Constrain on $Z_{\text{min}}$ by testing goodness-of-fit

$p = 2.18$ m = 6.8 fixed
uniform source distribution
d.o.f. of chi2 = 19
Upper limit of $Z_{\text{min}}$: $0.01 \sim 40$ Mpc (99.7% C.L.)
Summary and conclusions

• We searched compatibilities between 7 years TA SD energy spectrum and pure proton model for $E > 10^{18.2}$ eV.

• Data is compatible with this model. ($\chi^2/d.o.f. = 18.0/17$)

• Constrain on the fit parameters is obtained.
  \[ p = 2.18 - 0.14 + 0.08 \text{ (stat.+sys.)} \]
  \[ m = 6.8 - 1.1 + 1.6 \]
  \[ \Delta \log_{10} E = -0.04 \text{ (-9%) - 0.03 + 0.04} \]
  – Difference of propagation codes, LSS/uniform source distribution, IRB model make much smaller uncertainties than these errors.

• Constraint on $Z_{\text{min}}$ is obtained. : \( 0.01 \text{ (\sim 40 Mpc) in 99.7\% C.L.} \)
BackUp slides
Best fit result from pure iron source
fit range: $E > 10^{18.7} \text{ eV}$

$p = 1.7$, $E_{\text{max}} = 728$ EeV
Chi2/d.o.f. = 17/10 (stat. + sys.)
Combined with
FD mono energy spectrum \((E: 10^{18.0-18.2} \text{ eV})\)

Best fit chi2 = 25.9/19 for uniform

Above \(10^{18} \text{ eV}\)

With systematic uncertainty

\[ E > 10^{18} \text{ eV} \iff Z < \sim 0.8-0.9 \]

4-parameter fit

Best fit values: listed below

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p)</td>
<td>2.35</td>
</tr>
<tr>
<td>(m)</td>
<td>4.2</td>
</tr>
<tr>
<td>(\Delta \log_{10} E)</td>
<td>-0.06</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>arbitrary</td>
</tr>
</tbody>
</table>

\(\Delta \log E = \log E - \log E_{\text{obs}}\)

\(\alpha\): energy shift of the data

\(\alpha\): normalization of the flux
Combined 7 years (stat. + sys.)

TA SD 7 years (stat. + sys.)

\[ p = 2.35 - 0.04 + 0.03 \text{ (stat. + sys.)} \]
\[ m = 4.2 - 0.5 + 0.5 \]
\[ \Delta \log_{10} E = -0.06 - 0.03 + 0.06 \text{ Chi2 min./d.o.f.} = 25.9/19 \]
Constraint from secondary particles

SD spectrum: discussion of $z < \sim 0.7$

Assumption:
Evolution of UHECR sources $(1+z)^m$ continues to $z_{\text{max}}$

Secondary gamma-rays/neutrinos are calculated under this assumption.

Emax = 200 EeV is fixed for the calculation of IceCube limit.
Pierre Auger combined energy spectrum (ICRC2013)

$E > 10^{18.2}$ eV, index $p$: 1.5-2.7

with acceleration limit $E_{\text{max}}$

Best fit chi2 = 29.4/15 for uniform

Parameter | Best fit value
--- | ---
$p$ | 1.97
$m$ | 8.3
$\Delta \log_{10} E$ | +0.04
$E_{\text{max}}$ (eV) | $10^{19.90}$
$\alpha$ (normalization) | arbitrary

3% systematic uncertainties are added to the flux.

Chi2/d.o.f. > 10
Only with statistical errors

PRELIMINARY
of $(1 + z)^m$ is evaluated as P-values.