First Results from the IceTop Air Shower Array

Stefan Klepser
for the IceCube Collaboration
(see www.icecube.wisc.edu)

ECRS, September 2008
The IceCube Observatory
(as an Air Shower Detector)

**IceTop → Shower Detection**
- 80 Stations at 2 Ice-Č-Tanks (40 in 2008!)
- 2830 m altitude
- 125 m spacing
- \(3 \cdot 10^{14} < E < 10^{18} \text{ eV}\)
- \(A_{\text{tot}} \approx 1 \text{ km}^2\)

**IceCube → Muon Detection**
- 4800 DOMs
- Muon bundle detector
- \(E_{\text{muon}} > 100 \text{ GeV}\)
The IceCube Observatory
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- $E_{\mu\text{on}} > 100$ GeV

Stefan Klepser: First Results from the IceTop Air Shower Array
The IceTop Detector 2008
(present analysis)

T. Waldenmaier et al.,
NIM in Ph. Res. A,
588 (2008) 130–134

T. Gaisser et al.,
arXiv:0711.0353
Signal Processing

Finally: Conversion to Vertical Equivalent Muons

1 VEM ≈ 150 PE

calibration run, i.e. no coincidence conditions

L. Demirörs et al.,
arXiv:0711.0353

Stefan Klepser: First Results from the IceTop Air Shower Array
Lateral Pulse Height Distribution

- **Lateral Function**

\[ S(R) = S_{R0} \left( \frac{R}{R_0} \right)^{-\beta - \kappa \log_{10} \left( \frac{R}{R_0} \right)} \]

- charge expectation as a function of distance to shower axis

- **Fluctuations:**

  - Function of S

F. Kislat, dipl. thesis, HU Berlin

S. Klepser et al., arXiv:0711.0353
Resolution & Efficiency

Directional Resolution \( \sim 1.5^\circ \)
Energy Resolution (above 3 PeV) \( \sim 16\% \) in \( E \)

numbers given for zenith angles 0°-30°!
Analysis Strategies

1. Coincident Analysis
2. Surface Muon Counting Analysis
3. IceTop-only Analysis
Analysis Strategies

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Analysis Strategies

1. Coincident Analysis
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3. IceTop-only Analysis

Following slides...
Energy Response

Convolution:
\[ \vec{F} = \mathbf{R} \vec{C} \]
measured \hspace{1cm} true

Response Matrix

composition dependency!

[Graph showing energy response with labeled axes and data points]

Stefan Klepser: First Results from the IceTop Air Shower Array
Unfolding under Composition Assumptions

- 'Bayesian' and 'Gold' algorithms
- 3 Zenith bins
- Inconsistency between Zenith ranges

S. Klepser, PhD thesis, HU Berlin
Unfolding under Composition Assumptions

- 'Bayesian' and 'Gold' algorithms
- 3 Zenith bins
- Inconsistency between Zenith ranges

*Preliminary*

S. Klepser, PhD thesis, HU Berlin
Unfolding under Composition Assumptions

J. Hoerandel, “On the knee in the energy spectrum of cosmic rays,”

- ‘Bayesian’ and ‘Gold’ algorithms
- 3 Zenith bins
- Inconsistency between Zenith ranges

Sensitivity on Composition!

S. Klepser, PhD thesis, HU Berlin
Unfolding under Composition
Assumptions

R. Glasstetter *et al.*, “Analysis of electron and muon size spectra of EAS,”
in *Proc. 26th ICRC, Salt Lake City, USA, 1999.*

- ‘Bayesian’ and ‘Gold’ algorithms
- 3 Zenith bins
- Inconsistency between Zenith ranges

Sensitivity on Composition!

*S. Klepser,*
PhD thesis, HU Berlin
Quantitative Analysis

- Highest compatibility: Both mixed composition models

- Other Likelihood ratios:
  - Pure proton composition: $4 \cdot 10^{-8}$
  - Pure iron composition: $2 \cdot 10^{-14}$

- Complementary approach, independent of muon multiplicities in HE interactions!
Quantitative Analysis

- Highest compatibility: Both mixed composition models
- Other Likelihood ratios:
  - Pure proton composition: $4 \cdot 10^{-8}$
  - Pure iron composition: $2 \cdot 10^{-14}$
- Complementary approach, ~ independent of muon multiplicities in HE interactions!
Energy Spektrum
(Polygonato Assumption)

- Data Aug. 07 (26 Stations)
- Exposure: $3.86 \times 10^{11} \text{ m}^2 \text{ s sr}$
- 734982 Events
- $\sigma_{sys} \sim 11\%$ in E
- Comparably low flux or energy ($\sim 1.5 \sigma_{sys}$)
- $E_{knee} = 3.1(3) \text{ PeV}$
- $\gamma_1 = 2.71(7)$
- $\gamma_2 = 3.11(8)$

S. Klepser, PhD thesis, HU Berlin
Energy Spektrum
(Polygonato Assumption)

- Data Aug. 07 (26 Stations)
- Exposure: $3.86 \cdot 10^{11} m^2 s sr$
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S. Klepser,
PhD thesis, HU Berlin

S. Klepser, PhD thesis, HU Berlin
Outlook I: Coincident Analysis

More advanced:

- IceTop: e/m shower
- IceCube: HE muons

4 Parameters to analyse E and mass!

- Size & Spread of IceTop Event
- Size & Spread of IceCube Event
Outlook II: Surface Muon Counting

- looking for excess events in „outer region“ of an event

- muon peak in data and simulation!

- difference in p and Fe peak height!

- sensitivity to composition!

A. Lucke, dipl. thesis, HU Berlin
Summary

- First Energy Spectrum from 1 – 80 PeV
- Complementary Composition Sensitivity with IceTop only

Technical Outlook:
- Several Reducible Systematics
- Completion of IceTop in 2011

Analysis Outlook:
- Main Analysis: IceTop/IceCube Coincidences
- Yet Complementary Approach: Muon Counting
1 EeV
Spectral Parameters
(Polygonato Assumption)

\[ E_{\text{knee}} = 3.1 \pm 0.3 \text{ (stat.)} \pm 0.3 \text{ (sys.)} \text{ PeV} \]

\[ \gamma_1 = 2.71 \pm 0.07 \text{ (stat.)} \]

\[ \gamma_2 = 3.110 \pm 0.014 \text{ (stat.)} \pm 0.08 \text{ (sys.)} \]

<table>
<thead>
<tr>
<th></th>
<th>( E_{\text{knee}} )</th>
<th>(-\gamma_1)</th>
<th>(-\gamma_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KASCADE</td>
<td>4.0(8) – 5.7(1.6)</td>
<td>2.70(6)</td>
<td>3.10(7) – 3.14(6)</td>
</tr>
<tr>
<td>TIBET</td>
<td>3.8(1) – 4.0(1)</td>
<td>2.65(1) – 2.67(1)</td>
<td>3.08(5) – 3.12(1)</td>
</tr>
<tr>
<td>TUNKA</td>
<td>—</td>
<td>2.71(5)</td>
<td>3.22(5)</td>
</tr>
<tr>
<td>this work</td>
<td>3.1(4)</td>
<td>2.71(7)</td>
<td>3.11(8)</td>
</tr>
</tbody>
</table>
Unfolding

- **Inverts the effects of the response matrix**
  - No single solution
  - Depends on iteration or regularisation parameters

- **Used 2 iterative Algorithms:**
  - Gold
  - Bayesian, following D’Agostini
Mixed Composition Models

\[ \frac{dI}{d\log_{10} E} = I_{\text{PeV,lg}} \cdot \left( \frac{E}{1\text{ PeV}} \right)^{\gamma_1 + 1} \cdot \left( 1 + \left( \frac{E}{E_{\text{knee}}} \right)^\varepsilon \right)^{(\gamma_2 - \gamma_1)/\varepsilon} \]

Table 6.1: Constants of the input spectrum assumptions. $I_{\text{PeV,lg}}$ is given in terms of $10^{-6} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, $E_{\text{knee}}$ in PeV.

<table>
<thead>
<tr>
<th>model</th>
<th>A</th>
<th>Z</th>
<th>$I_{\text{PeV,lg}}$</th>
<th>$-\gamma_1$</th>
<th>$-\gamma_2$</th>
<th>$E_{\text{knee}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>only protons</td>
<td>H</td>
<td>1.0</td>
<td>5.47</td>
<td>2.66</td>
<td>3.08</td>
<td>3.08</td>
</tr>
<tr>
<td>H</td>
<td>1.0</td>
<td>1.0</td>
<td>1.61</td>
<td>2.71</td>
<td>$-\gamma_1 + 2.1$</td>
<td>4.49</td>
</tr>
<tr>
<td>He</td>
<td>4.0</td>
<td>2.0</td>
<td>1.71</td>
<td>2.64</td>
<td>$-\gamma_1 + 2.1$</td>
<td>$Z \cdot E_{\text{knee,H}}$</td>
</tr>
<tr>
<td>poly-gonato</td>
<td>CNO</td>
<td>14.2</td>
<td>0.673</td>
<td>2.67</td>
<td>$-\gamma_1 + 2.1$</td>
<td>$Z \cdot E_{\text{knee,H}}$</td>
</tr>
<tr>
<td>Mg-S</td>
<td>27.2</td>
<td>13.5</td>
<td>0.514</td>
<td>2.64</td>
<td>$-\gamma_1 + 2.1$</td>
<td>$Z \cdot E_{\text{knee,H}}$</td>
</tr>
<tr>
<td>Mn-Fe</td>
<td>55.7</td>
<td>25.9</td>
<td>0.997</td>
<td>2.57</td>
<td>$-\gamma_1 + 2.1$</td>
<td>$Z \cdot E_{\text{knee,H}}$</td>
</tr>
<tr>
<td>two-comp.</td>
<td>H</td>
<td>1.0</td>
<td>3.89</td>
<td>2.67</td>
<td>3.39</td>
<td>4.1</td>
</tr>
<tr>
<td>Fe</td>
<td>1.0</td>
<td>1.0</td>
<td>1.95</td>
<td>2.66</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>only iron</td>
<td>Fe</td>
<td>56.0</td>
<td>26.0</td>
<td>5.47</td>
<td>2.66</td>
<td>3.08</td>
</tr>
</tbody>
</table>
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Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>$\log_{10} E$</th>
<th>$\log_{10}(dI/d\log_{10} E)$</th>
<th>$E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>threshold</td>
<td>0.007</td>
<td>-</td>
<td>1.6%</td>
</tr>
<tr>
<td>snow, $\Omega_0$</td>
<td>0.009</td>
<td>-</td>
<td>2.1%</td>
</tr>
<tr>
<td>snow, $\Omega_1$</td>
<td>0.014</td>
<td>-</td>
<td>3.2%</td>
</tr>
<tr>
<td>snow, $\Omega_2$</td>
<td>0.017</td>
<td>-</td>
<td>3.9%</td>
</tr>
<tr>
<td>saturation, $E &lt; 30\text{ PeV}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>saturation, $E = 100\text{ PeV}$</td>
<td>0.02</td>
<td>-</td>
<td>4.6%</td>
</tr>
<tr>
<td>atmosphere</td>
<td>0.014</td>
<td>-</td>
<td>3.2%</td>
</tr>
<tr>
<td>instability</td>
<td>0.017</td>
<td>-</td>
<td>3.9%</td>
</tr>
<tr>
<td>interaction model</td>
<td>0.004</td>
<td>-</td>
<td>0.92%</td>
</tr>
<tr>
<td>calibration</td>
<td>0.03</td>
<td>-</td>
<td>6.9%</td>
</tr>
<tr>
<td>unfolding</td>
<td>-</td>
<td>0.014</td>
<td>1.90%</td>
</tr>
<tr>
<td>response matrix, $\Omega_0$</td>
<td>0.0015</td>
<td>0.007</td>
<td>1.01%</td>
</tr>
<tr>
<td>response matrix, $\Omega_1$</td>
<td>0.003</td>
<td>0.011</td>
<td>1.6%</td>
</tr>
<tr>
<td>response matrix, $\Omega_2$</td>
<td>0.004</td>
<td>0.015</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

$\sum: \sim 9 - 11\%$ in $E$

Technical issues of the simulation

Calibration
IceTop Tank Response

Tank response depends on particle type and energy

→ Average tank responses $S_j(E)$ for all particles types $j$ abundant in air showers were parametrised

- $e^-$
- $\mu^-$
- No cascades
- Hadronic cascades

$\frac{\text{tank signal}}{\text{VEM}}$ vs $\log_{10}(E/\text{GeV})$
Backup: Fits on Raw Spectrum, Folded Raw Spectra

Table 6.3: Parameters of the raw spectra (see eq. 6.1). $I_{\text{PeV,lg}}$ is given in terms of $10^{-6}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$, $E_{\text{knee}}$ in PeV.

<table>
<thead>
<tr>
<th>Zenith range</th>
<th>$I_{\text{PeV,lg}}$</th>
<th>$-\gamma_1$</th>
<th>$-\gamma_2$</th>
<th>$E_{\text{knee}}$</th>
<th>$\varepsilon$</th>
<th>$\chi^2/\text{ndf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ - 30^\circ$</td>
<td>3.24(7)</td>
<td>2.68(9)</td>
<td>2.98(2)</td>
<td>2.0(5)</td>
<td>3.2(1.5)</td>
<td>30.1/34</td>
</tr>
<tr>
<td>$30^\circ - 40^\circ$</td>
<td>3.19(3)</td>
<td>-</td>
<td>3.079(14)</td>
<td>-</td>
<td>-</td>
<td>40.9/30</td>
</tr>
<tr>
<td>$40^\circ - 46^\circ$</td>
<td>3.24(12)</td>
<td>-</td>
<td>3.13(3)</td>
<td>-</td>
<td>-</td>
<td>27.3/25</td>
</tr>
</tbody>
</table>
Backup: Threshold Definition

- Done for each Zenith bin
- Results:

<table>
<thead>
<tr>
<th>Zenith Range</th>
<th>Raw</th>
<th>Unfolded</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° - 30°</td>
<td>-0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>30° - 40°</td>
<td>0.30</td>
<td>0.50</td>
</tr>
<tr>
<td>40° - 46°</td>
<td>0.55</td>
<td>0.75</td>
</tr>
</tbody>
</table>

- Additional tolerance for unfolded spectra: 2 x width of response matrix
\[ \frac{dI}{d\log_{10} E} = I_{\text{PeV},\lg} \cdot \left( \frac{E}{1 \text{ PeV}} \right)^{\gamma_1 + 1} \cdot \left( 1 + \left( \frac{E}{E_{\text{knee}}} \right)^\varepsilon \right)^{(\gamma_2 - \gamma_1)/\varepsilon} \]

Table 8.4: Knee fit parameters of all 12 unfolded spectra, as defined in eq. 6.1. \( I_{\text{PeV},\lg} \) is given in terms of \( 10^{-6} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \), \( E_{\text{knee}} \) in PeV.

<table>
<thead>
<tr>
<th>model</th>
<th>( \theta ) bin</th>
<th>( I_{\text{PeV},\lg} )</th>
<th>(-\gamma_1)</th>
<th>(-\gamma_2)</th>
<th>( E_{\text{knee}} )</th>
<th>( \varepsilon )</th>
<th>( \chi^2/\text{ndf} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>only protons</td>
<td>( \Omega_0 )</td>
<td>3.61(10)</td>
<td>2.66(8)</td>
<td>3.05(2)</td>
<td>2.8(3)</td>
<td>5.8(3.4)</td>
<td>14.2/14</td>
</tr>
<tr>
<td></td>
<td>( \Omega_1 )</td>
<td>3.23(5)</td>
<td>-</td>
<td>3.08(3)</td>
<td>-</td>
<td>-</td>
<td>11.6/12</td>
</tr>
<tr>
<td></td>
<td>( \Omega_2 )</td>
<td>3.3(2)</td>
<td>-</td>
<td>3.17(6)</td>
<td>-</td>
<td>-</td>
<td>5.7/9</td>
</tr>
<tr>
<td>poly-gonato</td>
<td>( \Omega_0 )</td>
<td>4.21(9)</td>
<td>2.71(7)</td>
<td>3.12(3)</td>
<td>3.1(3)</td>
<td>4.7(2.7)</td>
<td>9.5/13</td>
</tr>
<tr>
<td></td>
<td>( \Omega_1 )</td>
<td>3.92(7)</td>
<td>-</td>
<td>3.10(2)</td>
<td>-</td>
<td>-</td>
<td>14.2/12</td>
</tr>
<tr>
<td></td>
<td>( \Omega_2 )</td>
<td>4.2(2)</td>
<td>-</td>
<td>3.13(4)</td>
<td>-</td>
<td>-</td>
<td>5.2/9</td>
</tr>
<tr>
<td>two-comp.</td>
<td>( \Omega_0 )</td>
<td>4.43(9)</td>
<td>2.75(6)</td>
<td>3.12(3)</td>
<td>3.1(3)</td>
<td>5.4(3.3)</td>
<td>9.7/13</td>
</tr>
<tr>
<td></td>
<td>( \Omega_1 )</td>
<td>4.15(5)</td>
<td>-</td>
<td>3.11(2)</td>
<td>-</td>
<td>-</td>
<td>16.2/12</td>
</tr>
<tr>
<td></td>
<td>( \Omega_2 )</td>
<td>4.6(2)</td>
<td>-</td>
<td>3.16(4)</td>
<td>-</td>
<td>-</td>
<td>5.4/9</td>
</tr>
<tr>
<td>only iron</td>
<td>( \Omega_0 )</td>
<td>8.39(4)</td>
<td>3.074(9)</td>
<td>3.29(2)</td>
<td>3.7(3)</td>
<td>2.7(7.0)</td>
<td>11.7/13</td>
</tr>
<tr>
<td></td>
<td>( \Omega_1 )</td>
<td>9.91(9)</td>
<td>-</td>
<td>3.28(2)</td>
<td>-</td>
<td>-</td>
<td>21.7/13</td>
</tr>
<tr>
<td></td>
<td>( \Omega_2 )</td>
<td>14.2(7)</td>
<td>-</td>
<td>3.37(4)</td>
<td>-</td>
<td>-</td>
<td>6.3/9</td>
</tr>
</tbody>
</table>
Energy Estimation

\[ l_{E_0}(x, l_{S_{100}}) = p_0 + p_1 x - \sqrt{p_2 + p_3 x - p_4 l_{S_{100}}}. \]

- \( p_0 = 24.0269 \)
- \( p_1 = 11.3414 \)
- \( p_2 = 459.884 \)
- \( p_3 = 805.717 \)
- \( p_4 = 69.9528 \)

\[ x = \sec \theta \]

→ Analytical Function to assign \( S_{\text{ref}} \) and \( \theta \) an energy estimator for proton assumption

S. Klepser et al., arXiv:0711.0353
Quantitative Analysis

- Calculating Likelihood Ratios

- Clear Preference of mixed composition models!

- Complementary approach, ~ independent of muon multiplicities in HE interactions!

<table>
<thead>
<tr>
<th></th>
<th>only protons</th>
<th>poly-gonato</th>
<th>two-components</th>
<th>only iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{34\text{le}} )</td>
<td>3.34(12)</td>
<td>4.05(10)</td>
<td>4.26(11)</td>
<td>8.8(5)</td>
</tr>
<tr>
<td>( \chi^2/\text{n df} )</td>
<td>10.0/2</td>
<td>6.9/2</td>
<td>8.4/2</td>
<td>257/2</td>
</tr>
<tr>
<td>prob.</td>
<td>6.7 \cdot 10^{-3}</td>
<td>3.2 \cdot 10^{-2}</td>
<td>1.53 \cdot 10^{-3}</td>
<td>6.9 \cdot 10^{-11}</td>
</tr>
<tr>
<td>(-\gamma_2)</td>
<td>3.07(2)</td>
<td>3.110(14)</td>
<td>3.120(14)</td>
<td>3.294(19)</td>
</tr>
<tr>
<td>( \chi^2/\text{n df} )</td>
<td>3.9/2</td>
<td>0.61/2</td>
<td>1.25/2</td>
<td>4.1/2</td>
</tr>
<tr>
<td>prob.</td>
<td>0.145</td>
<td>0.74</td>
<td>0.54</td>
<td>0.126</td>
</tr>
<tr>
<td>total prob.</td>
<td>9.8 \cdot 10^{-1}</td>
<td>2.3 \cdot 10^{-2}</td>
<td>8.2 \cdot 10^{-3}</td>
<td>8.7 \cdot 10^{-12}</td>
</tr>
</tbody>
</table>

Likelihood Ratios
Resolution & Efficiency

~1.5°

~0.094 km²

~9 m

~16% in E

full acceptance >1 PeV

~0.094 km²

numbers given for zenith angles 0°-30°!
Quantitative Analysis

- Calculating Likelihood Ratios

  - Clear Preference of mixed composition models!

  - Complementary approach, \( \sim \) independent of muon multiplicities in HE interactions!