Outline

- The Auger Observatory
- Measurement of Atmospheric Aerosols
- Comparison of Atmospheric Models
- Horizontal Uniformity
- Errors Due to Aerosol Parameters
- Problems
- Summary of Results
- Conclusions
The Auger Observatory

- Located in Malargüe, Argentina
- Built to Detect Ultra-High Energy Cosmic Rays (E > $10^{18}$ eV)
- Currently, we do not know the origin of the highest energy cosmic rays
- GZK cutoff predicts that particles with E > $10^{20}$ eV must originate within 50 Mpc of Earth
The Auger Observatory

- Uses two different detection methods
- Surface detector array of water Cherenkov tanks spread out over 3000 km²
- Four fluorescence detector locations at the edge of the SD array
- The atmosphere is used as a calorimeter for measuring particle energy.
Map of the Auger Observatory
Fluorescence Detectors
Example FD Event

Angle \sim 60 \text{ deg}
$X_{\text{max}}$

$E \sim 20$ EeV

$\chi^2/\text{Ndf} = 144.44/124$
Example Event #2

Energy: ~10 EeV
Angle: ~60 deg
Measurement of Atmospheric Aerosols
Measurement of Atmospheric Aerosols

- Measurements affected by both molecular and aerosol elements of the atmosphere
- Molecular effects well described by Rayleigh scattering.
- Aerosols can’t generally be described analytically
- Several parameters must be measured at each FD site to account for aerosols
Measurement of Atmospheric Aerosols

- Central Laser Facility (CLF) is used to measure the VAOD every hour.
- An APF light source is near each FD site to measure the differential scattering cross-section.
- Four Lidar stations provide additional VAOD data.
Measurement of Atmospheric Aerosols

- Aerosol Phase Function/Scattering Cross-Section

\[ P(\theta) = \frac{1 - g^2}{4\pi} \left( \frac{1}{(1 + g^2 + 2g \cos \theta)^{3/2}} + f \frac{3\cos^2 \theta - 1}{2(1 + g^2)^{3/2}} \right) \]

S.Y. BenZvi et al., submitted to Astroparticle Physics (arXiv:0704.0303v1 [astro-ph])
Measurement of Atmospheric Aerosols

- VAOD and Extinction Coefficient

- VAOD Wavelength Dependence

\[ \tau(h) = \frac{-\ln(L(h)/L_{ref}(h))}{1 + \csc \varepsilon} \]

\[ \tau(h) = \int_{h_{ground}}^{h} \alpha(h')dh' \]

Transmission: \( T_{\varepsilon}(h) = e^{-\tau(h)} \)

\[ \tau(\lambda) = \tau_0 \left( \frac{\lambda_0}{\lambda} \right) \]

![Graph showing vertical aerosol optical depth versus height above sea level]
Event Reconstruction

- Used mainly “Golden Hybrid” dataset
- Events are reconstructed using C++ software controlled by XML files.
- Software retrieves aerosol information from a MySQL database.
Comparison of Parametric Atmospheric Model to Aerosol Database

- Assume exponential form for VAOD and $\alpha$.
- Use to see how well a simple model approximates the measured data.

\[
\tau(h) = \frac{H}{L} \left( e^{-h_0/H} - e^{-h/H} \right)
\]

\[
\alpha(h) = \frac{1}{L} e^{-h/H}
\]
Measurement of Horizontal Uniformity

- When data is missing, software copies it from next nearest site
- Reconstruction also assumes that VAOD is constant in the area around each FD
- Events reconstructed after switching databases for Coihueco and Los Leones
- Systematic energy shifts of -2% (underestimate) at Los Leones and +2% (overestimate) at Coihueco
Measurement of Horizontal Uniformity
Measurement of Errors Due to Uncertainties of Aerosol Parameters

- VAOD, scattering cross-section and VAOD wavelength dependence measured
- Errors propagated by varying the parameters by +/-1σ
- Found relative error on energy and absolute error on $X_{\text{max}}$.
- Total error: ~5% on energy and ~4 g/cm² on $X_{\text{max}}$. 
Uncertainties from Aerosol Parameters
Problems

- Secondary maximum on VAOD plot due to non-physical VAOD limits in database.
- Some data with no changes were removed.
- VAOD database created from CLF light profiles.
- Original CLF error analysis software must be improved.
## Summary of Results

<table>
<thead>
<tr>
<th>Error Source</th>
<th>ΔE / E (%)</th>
<th>ΔX_{max} (g cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hor. Uniformity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| -Los Leones         | Systematic shift: -2  
|                     | Width: 5    | Systematic Shift: -2  
|                     |             | Width: 7        |
| -Coihueco           | Systematic Err: +2    
|                     | Width: 5    | Systematic Shift: +2    
|                     |             | Width: 9        |
| VAOD                | 4.8        | 3.3             |
| Phase Function      | 0.52       | 0.54            |
| Wavelength          | 1.5        | 2.2             |
| TOTAL STAT. ERR.    | 5          | 4               |
| Parametric Model    |            |                 |
| -Systematic Shift   | -4.4       | -0.3%           |
| -Width              | 9.7        | 1.3%            |
Conclusions

- Statistical errors from measurements smaller than those from parametric model
- Systematic errors also smaller, affect fewer events
- Aerosol database appears to be the best way to minimize the errors in measurements
Conclusions/Future Work

- Errors dominated by VAOD uncertainty
- On very clean nights (i.e. few, if any aerosols), VAOD reconstruction can fail
- Once VAOD software completed, we should repeat error propagation.
- However, no significant changes are expected.
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