Completing & Improving the TeV Cosmic-Ray Sky with HAWC & IceCube

TeVPA 2017
Columbus, Ohio
The TeV Cosmic-Ray Sky

• Difficult to measure
  • Only ground-based detectors have detections
  • Background and weak signal are intertwined spatially
  • Ground detectors are currently limited to only measuring anisotropies in direction of Earth’s rotation (RA)
  • Hard to interpret
    • Need complete sky to properly measure
    • Missing anisotropy along Declination (m=0 modes)
    • Are deficits and excesses equally important?

• Recent Developments
  • Maximum-likelihood technique which uses direct integration to find unbiased background
  • Cosmic-ray energy estimation for ground detectors is evolving. Not just using number of hit detectors
  • Complete two-dimensional descriptions
Unbiased Background Estimation

- For a detector with a constant acceptance as a function of time, the expected result of an isotropic flux would be … well … isotropic!

- Adding a dipolar signal to the isotropic flux will bias background estimation methods that are based upon data (e.g. time-scrambling, direct integration) and over long periods (Long \( \Delta t \)).

- With an iterative approach, this bias can be removed (right diagram) by fitting the detector response and anisotropy simultaneously.
Limitations (Ground-based)

- Experiments are limited currently to measuring anisotropies in direction of Earth rotation (RA)
- For a pure dipole anisotropy, this greatly affects the measurable strength
- Measured strength goes to zero as the orientation goes to the poles (90°)
Unbiased Background / Limitations

- Simulated dipole anisotropy reconstructed using method of (M. Ahlers et al. 2016)
- Blue line is the best one can do with ground-based instrument
- Red/blue points show fit from healpy software

Method improves with iteration (light to dark red)

healpy fit must be corrected because of limited sky coverage (blue)

healpy: HEALPix + Python
HEALPix: sphere pixelation + sky map routines
HAWC Results

- Background method applied to 400 full, sidereal days of HAWC data
- Applied strong cut (2% pass) to reach unprecedented energy resolution for this measurement. Harsh cuts provide highly diagonalized mixing matrix (verified on CR spectrum/Moon shadow).
- Described using full 2D dipole fit (truncated)

<table>
<thead>
<tr>
<th>Energy [TeV]</th>
<th>Amplitude [$\times 10^{-4}$]</th>
<th>Phase</th>
<th>$a_{1,1}$ [$\times 10^{-4}$]</th>
<th>$a_{1,-1}$ [$\times 10^{-4}$]</th>
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<tbody>
<tr>
<td>1.4 (0.8)</td>
<td>7.5 ± 0.6</td>
<td>33.3° ± 4.4°</td>
<td>−18.1 ± 1.7</td>
<td>−11.9 ± 1.7</td>
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<tr>
<td>2.4 (1.5)</td>
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<td>3.5 (2.5)</td>
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<td>6.1 (4.3)</td>
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<td>44.0° ± 1.2°</td>
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<td>29.9 (18.2)</td>
<td>14.4 ± 0.7</td>
<td>29.9° ± 2.6°</td>
<td>−36.2 ± 1.9</td>
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<td>70.0 (42.1)</td>
<td>5.4 ± 0.7</td>
<td>41.9° ± 7.0°</td>
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HAWC Results

- Non-dipolar structure is obviously present
- Northward strengthening of ‘Region A’
- Strong quadrupole component at low energies
- Run out of statistics in last bin…

*Preliminary*

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Comparison to other experiments

- Cause of Discrepancies?
- Energy scale? ~10%
- Use of 2D Fit?
- CR composition sensitivity? (IceCube is underground...)

- Compares favorable with other experiments when considering uncertainty in energy
1st Ever All-Sky* TeV Cosmic-Ray Map

- Combining data from HAWC (North) and IceCube (South) gives almost full sky coverage
- Data is energy-matched to be meaningful
- Same method as with HAWC-only data

1st Ever All-Sky* TeV Cosmic-Ray Map

- Dipolar feature connects well,
- Region A does not continue South at these energies
- IceCube features are more significant (more data)
- Combined map has more power in the dipole due to better sky coverage (most of this comes from the HAWC data)
1st Ever All-Sky* TeV Cosmic-Ray Map

- Combined map is then fit with truncated spherical harmonic series ($l \leq 3$)
- Dipole amplitude and phase can be compared against other experiments

adopted from M. Ahlers et al. ArXiv:1612.01873
Summary

• Our descriptions of the TeV Sky are improving!
  • Background techniques are mature
  • Energy estimation is maturing
  • Results are being reported with full two-dimensionality

• A full-sky* picture is available!
Combined Sky Map
Large-scale Removed (right)