Studying the Temporal Variation of the Cosmic-Ray Sun Shadow Using IceCube Data

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International Cosmic Ray Conference 2019,
Madison

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Motivation

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Motivation

- Number of observed secondary muons from directions around Moon/Sun is reduced due to blocked cosmic rays (CRs)
- Shadowing effect measured with high statistical significance by several experiments (e.g. Tibet, ARGO-YBJ, HAWC)
- Moon shadow serves as a standard candle (known apparent size, no magnetic field)
- Sun shadow serves as indirect measurement of solar magnetic field → Compare models
  - Tibet, PRL 111, 2013: ~10 TeV CRs, measuring air showers
  - Here: ~55 TeV CRs, measuring atmospheric muons
Analysis Method
Analysis Method

- Right ascension/decl. relative to Moon/Sun
- On- and off-source windows (6° × 6° each)
- Bin-wise (0.1° × 0.1°) relative deficit in on-source region in a 2D grid
- Visualize the shadow:
  - Boxcar smoothing (0.7° smoothing radius)
  - Determine center of gravity (COG)
- Numerical analysis:
  - Relative deficit within 1.0° around COG

Relative coordinates:
\[
\Delta \alpha = \alpha_{\mu} - \alpha_{S/M} \\
\Delta \delta = \delta_{\mu} - \delta_{S/M}
\]

Relative deficit:
\[
\frac{\Delta N}{\langle N \rangle} = \frac{N_{on} - \langle N_{off} \rangle}{\langle N_{off} \rangle}
\]
Results: Part I
Results: Moon

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Results: Moon

- Cosmic rays „see“ Moon as unmagnetized ball
- In 2D: disk-like cosmic-ray sink
- Expect relative deficit to depend on average elevation and apparent Moon radius

<table>
<thead>
<tr>
<th>Object</th>
<th>Year</th>
<th>Events / $10^6$</th>
<th>Avg. Elev. / °</th>
<th>Radius / °</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>2010/11</td>
<td>7.9</td>
<td>22.1</td>
<td>0.261</td>
</tr>
<tr>
<td>Moon</td>
<td>2011/12</td>
<td>7.7</td>
<td>20.7</td>
<td>0.270</td>
</tr>
<tr>
<td>Moon</td>
<td>2012/13</td>
<td>6.4</td>
<td>18.9</td>
<td>0.274</td>
</tr>
<tr>
<td>Moon</td>
<td>2013/14</td>
<td>4.5</td>
<td>17.7</td>
<td>0.272</td>
</tr>
<tr>
<td>Moon</td>
<td>2014/15</td>
<td>3.8</td>
<td>16.9</td>
<td>0.265</td>
</tr>
<tr>
<td>Moon</td>
<td>2015/16</td>
<td>4.1</td>
<td>16.7</td>
<td>0.257</td>
</tr>
<tr>
<td>Moon</td>
<td>2016/17</td>
<td>5.1</td>
<td>17.2</td>
<td>0.251</td>
</tr>
</tbody>
</table>

Key to (almost) all questions: simulations
- Exclude events with primary cosmic-ray direction within Moon disk

Can we explain this variation?
Results: Moon

\[ \chi^2/\text{ndf} = 8.2/7 = 1.2 \]
Results: Sun
Results: Sun

$\chi^2 / \text{ndf} = 73/7 = 10.4$
Results: Sun

- Relative deficit of Sun shadow varies with time despite constant parameters (solar activity?)

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</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>2010/11</td>
<td>9.0</td>
<td>22.1</td>
<td>0.271</td>
</tr>
<tr>
<td>Sun</td>
<td>2011/12</td>
<td>13.1</td>
<td>21.8</td>
<td>0.271</td>
</tr>
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<tr>
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<td>2016/17</td>
<td>13.3</td>
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- Unmagnetized solar disk model excluded at $\sim 7\sigma$
- Correlation of relative deficit with solar activity is likely ($p=3\%$)
- Linear dependence of relative deficit on SSN preferred at $\sim 6\sigma$

Sunspot data from the World Data Center SILSO, Royal Observatory of Belgium, Brussels
Solar Magnetic Field
Modeling the Solar Magnetic Field

- Synoptic magnetograms measure the photospheric magnetic field strength

- Two coronal magnetic field models:

- Both use „source surface“ where all magnetic field lines are assumed to be purely radial


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Results: Part II
Results: Sun

\[ \chi^2 / \text{ndf} = 21.9 / 7 = 3.1 \]
\[ \chi^2 / \text{ndf} = 20.2 / 7 = 2.9 \]
Results: Sun

- Observed variation in the data reproduced by simulations
- Years with low solar activity not well-described by models
- CSSS and PFSS models preferred over solar disk, but tensions exist
- Neglected/smaller effects:
  - (Latitude-dependent) solar wind velocity profile
  - Geomagnetic field
  - Earth-directed coronal mass ejections (ECMEs)
  - Different magnetogram normalizations
Summary

- IceCube detects Moon and Sun shadows with high statistical significance.
- Moon shadow consistent with simulations based on lunar disk size and average elevation.
- Sun shadow varies in correlation with sunspot number (p-value for non-correlation: ~3%).
- PFSS/CSSS models clearly preferred over solar disk model.
- Evaluating solar magnetic field models using IceCube data — for the first time!

The cosmic-ray sun shadow in IceCube is a useful new tool for solar physics.

Thank you for your attention!
The IceCube Neutrino Observatory

- IceCube is a neutrino detector at the geographic South Pole.
- Instrumented volume: \( \sim 1 \text{km}^3 \)
- 5160 digital optical modules deployed on 86 strings.
- Large amount of data: muon trigger rate of about 2100 events per second.
- Here: atmospheric muons constitute data sample.
The Moon/Sun Shadow Data Sample

- IceCube uses filters, that follow the path of Moon/Sun across the sky
- Filters are active, when Moon/Sun are above the horizon
- Full azimuth band (360°) for +/-10° declination band around object
- Quality cuts on track reconstruction parameters
- Median angular error: ~ 0.75°
- Median energy: ~ 55 TeV
On- and off-source windows
Solar Magnetic Field

Magnetograms
- Global Oscillation Network Group (GONG)
- Synoptic Optical Long-term Investigations of the Sun (SOLIS)

Input to

Potential Field Models
- Potential Field Source Surface Model (PFSS)
- Current Sheet Source Surface Model (CSSS)

Full Model of the Solar Magnetic Field between Sun and Earth

Tabulated Output:
- Coronal magnetic field between photosphere and source surface

Parker Spiral:
- Heliospheric magnetic field beyond source surface based on solar wind velocity model
Simulations: Basic Principle

On-source window

Event by event information

Relative coordinates

Calculate space angle

Modify weights

Relative coordinates

Modify weights

Equatorial to ecliptic coordinates

Simulated Moon/Sun shadow

On-source window

Event by event information

Relative coordinates

Backtrack all primaries until they hit/pass the Sun

Passing probability

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Simulating the Sun shadow

1 Carrington Rotation ~ 27.3 days

\[ p = \frac{n_{\text{pass}}}{n_{\text{total}}} \]

\[ wI = p \cdot w \]

1/4 hits \(\rightarrow p=0.75\)

For the Moon, \(p\) is a step function depending on \(r\)

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Coordinate transformations

```python
>>> from astropy import units as u
>>> from astropy.coordinates import SkyCoord

>>> c_icrs = SkyCoord(ra=10.68458*u.degree, dec=41.26917*u.degree, frame='icrs')
>>> c_icrs.galactic
<SkyCoord (Galactic): (l, b) in deg
 (121.17424181, -21.57288557)>
```