Study of Earth’s Stratospheric $\gamma$-Ray Emission in Geographical Coordinates with *Fermi* LAT

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Cosmic-Ray (CR)-Induced $\gamma$-Ray Emission of Earth

- How Earth appears in $\gamma$ ray for LAT
- Physical limb: $\Theta_{\text{Zen}} \approx 113^\circ$
- Emission peak: $\Theta_{\text{Zen}} \approx 112^\circ$ (altitude $\approx 50$ km)
• Peak of profile moved over time due to LAT orbital decay
• Use data from $\text{Peak} < \Theta_{\text{Zen}} < \text{Peak} + 2.0^\circ$ because we can assume that these $\gamma$ rays were produced at ~50-km altitude (top of stratosphere)
• $\gamma$ rays with $\Theta_{\text{Zen}} < \text{peak}$ were produced at unknown altitude
Earth's magnetic field blocks CRs below cutoff rigidities for certain locations

Vertical Geomagnetic Cutoff Rigidity

Rigidity = momentum / charge

Unit in GV
Data Set

- Jan 1, 2009 to May 30, 2018
- Rocking angle > 55°
- Energy = 200 MeV – 20 GeV
- Peak < $\Theta_{\text{Zen}}$ < Peak + 2.0°
- Incident angle < 65°
- Event selection = P8R2 Source V6
- Divide $\Phi_{\text{Nadir}}$ into 4 sections: N, E, S, W
Earth's Stratospheric $\gamma$-Ray Intensity Maps

(a) North

(b) East

(c) South

(d) West

Madlee, et al., JGR: Space Phys., 125 (2020)

Horizontal cutoff rigidity contours (GV)
Earth's $\gamma$-Ray Intensity vs Cutoff Rigidity

- Cutoff rigidity = minimum rigidity for CRs to reach the top of atmosphere at certain location (here for the horizontal direction)
- Earth's $\gamma$-ray intensity decreases for increasing cutoff rigidity because CR flux falls steeply with energy
- Minimum CR energy to produce $\gamma$ rays = the lower bound of the energy bin

Madlee, et al., JGR: Space Phys., 125 (2020)
Earth's Stratospheric $\gamma$-Ray Yield between 0.2 – 20 GeV

- Assume only CR protons and He, and $Y_{\text{He}} = 1.6 Y_p$.

- Interpretation: $Y_p = \text{Earth's } \gamma$-ray intensity per rigidity emitted from the stratosphere ($\sim 50$ km) as observed by the LAT divided by CR proton intensity per rigidity near Earth.

\[ Y_p(P) = -\frac{[dI/dP_c]_P}{J_p(P) + 1.6 J_{\text{He}}(P)} \]

\[ I(P_c) = \int_{P_c}^{\infty} \sum_i J_i(P) Y_i(P) dP \]

\[ \text{CR spectrum of particle } i \text{ at rigidity } P \]

\[ \text{$\gamma$-ray yield function for particle } i \text{ at rigidity } P \]

\[ \text{$\gamma$-ray intensity above cutoff rigidity } P_c \text{ observed by LAT} \]

Madlee, et al., JGR: Space Phys., 125 (2020)
Earth's $\gamma$-Ray Spectrum

$I_{\text{max}} = \text{Intensity during solar maximum period (2012 – 2017)}$

$I_{\text{min}} = \text{Intensity during solar minimum period (2009 – 2011 and 2017 – 2018)}$

Madlee, et al., JGR: Space Phys., 125 (2020)
Summary

- Using *Fermi* LAT data, we obtain the first geographical maps of the Earth's stratospheric $\gamma$-ray emission from CR air showers.
- We study associations between $\gamma$-ray emission intensity and the geomagnetic cutoffs for CRs.
- We calculate the stratospheric $\gamma$-ray yield function between 0.2 – 20 GeV due to CR protons.
- This work presents unique data on CR interactions with the heliosphere, the geomagnetic field, and the atmosphere.

Madlee, et al., JGR: Space Phys., 125 (2020)
Back Up 2: Atmospheric Column Density

Abdo, et al., PRD 80, 122004 (2009)

The graph shows the integrated column density in grams per square centimeter ($g \text{ cm}^{-2}$) as a function of the nadir angle ($\Theta_{\text{Nadir}}$) in degrees. The data points are labeled as follows:

- Black circles: Fermi-LAT above 3.6 GeV (scaled)
- Open circles: Fermi-LAT above 3.6 GeV deconvolved (scaled)
- Dashed line: NRLMSISE-00
- Solid line: 6.8 km scale height exponential

The y-axis represents the integrated column density ranging from $10^{-5}$ to $10^3$ $g \text{ cm}^{-2}$, while the x-axis represents the nadir angle ranging from 66 to 69.5 degrees.