Simulating Earth-limb Gamma Rays

Ben Y. O. Xu [1] Kenny C. Y. Ng [1] Chingam Fong [1] Zhe Li [2]

[1]Department of Physics, The Chinese University of Hong Kong

[2]Institute of High Energy Physics, Chinese Academy of Sciences

benxu@link.cuhk.edu.hk

September 1, 2026

Overview

- Produced by interactions between cosmic rays (CR) and the Earth's atmosphere.

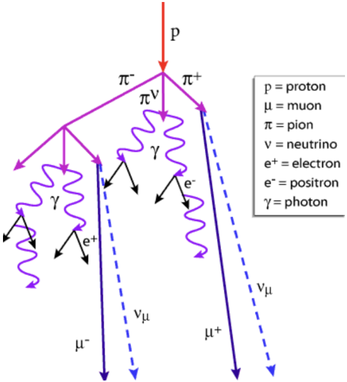
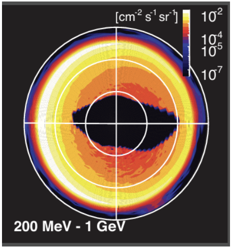


Image from https://www.hawc-observatory.org/science/cosmicrays.php

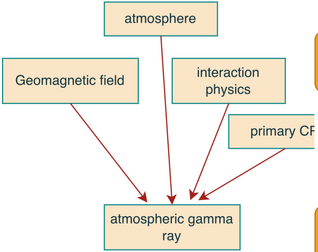
Motivation for Simulating Atmospheric γ-rays

- Atmospheric γ-rays act as a strong background for astronomical observations

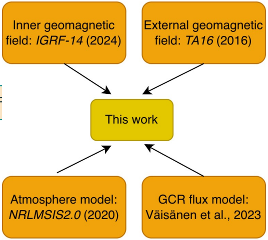


γ-ray intensity viewed from Fermi-LAT (Abdo et al., 2009)

- Testing ground for physics models

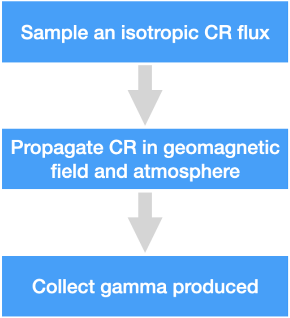


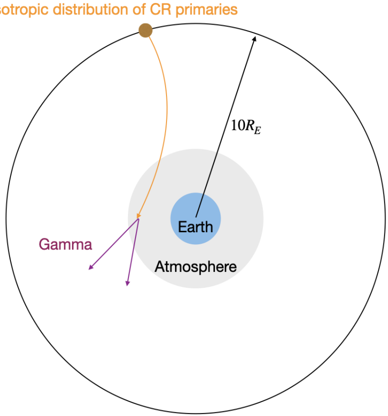
- No simulations using modern models have been conducted in over two decades



A Simple Simulation

- A naive approach to the simulation:

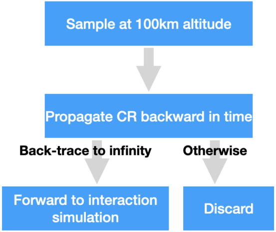


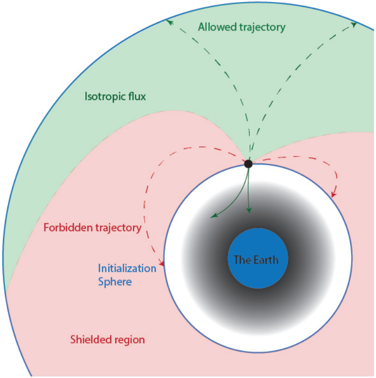


- However, many cosmic rays miss the atmosphere and do not produce γ-rays.

Back-tracing

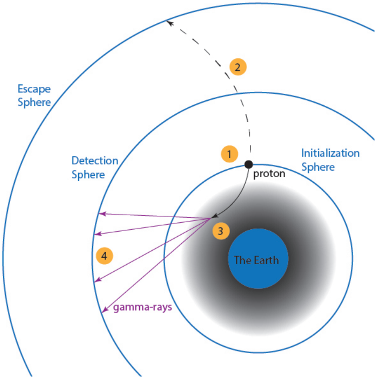
- Geomagnetic field modeled up to a distance of $10R_E$ (Escape sphere) using:
  - Internal geomagnetic field: $\mathrm{IGRF\text{-}14}$ model (International Association of Geomagnetism and Aeronomy, 2024)
  - External field: $\mathrm{TA16}$ (Tsyganenko et al., 2016)
- Liouville's theorem: if the particle flux at infinity is isotropic, the particle flux at an arbitrary point is the same as at infinity along a set of allowed trajectories, and 0 along the forbidden trajectories
- Recipe:





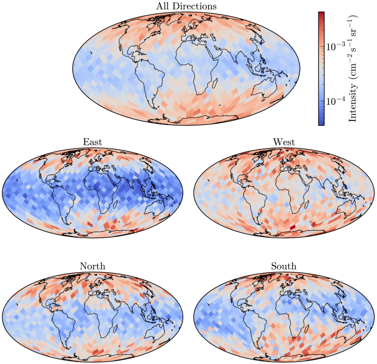
A simplified illustration

- The atmosphere is modeled as 200 concentric spherical shells extending from sea level to an altitude of 100 km
- Each shell has a uniform thickness of 0.5 km
- Shells are divided into an 18×18 grid with equal intervals of latitude (10°) and longitude (20°)
- The NRLMSIS2.0 atmospheric model (Emmert et al., 2021) calculates the densities of hydrogen, helium, oxygen, nitrogen, and argon at each grid's midpoint
- Particle interactions are modeled using the FTFP_BERT physics list in GEANT4 (Allison et al., 2016)



Benchmarking Against Fermi-LAT Observations

- Fermi LAT γ-ray observations: between June and September 2008 (Abdo et al., 2009)
- Simulation parameters: using input parameters corresponding to 00 : 00 UTC on 12th June 2008
- Simulated γ-ray flux was extracted at Fermi's orbital altitude and inclination:
  - Altitude = 565 km (Atwood et al., 2009)
  - Inclination within 25.5° (Atwood et al., 2009)

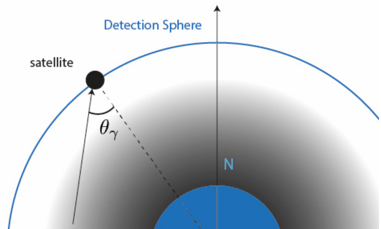


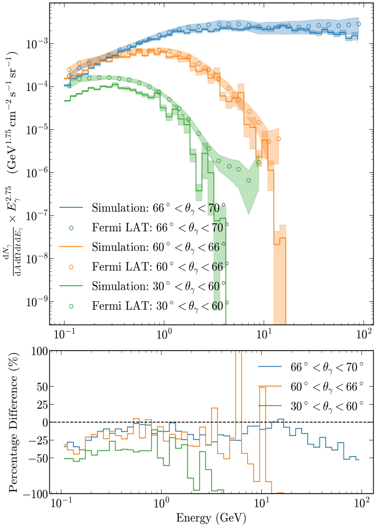
Remarks:

- Fermi-LAT does not record data inside the South Atlantic Anomaly (SAA) (Atwood et al., 2009).
- Orbital precession introduces non-uniform exposure across geographic locations and pointing directions.
- Our current simulation neither masks the SAA region nor applies exposure weighting to the flux.

Energy Spectrum

- Reproduces the general spectral shape across all evaluated nadir angle (θ_γ) intervals
- $\sim 25\%$ discrepancy at $66^\circ < \theta_\gamma < 70^\circ$ and $60^\circ < \theta_\gamma < 66^\circ$
- $\sim 50\%$ discrepancy at $30^\circ < \theta_\gamma < 60^\circ$
- The exact cause of this systematic discrepancy remains under investigation





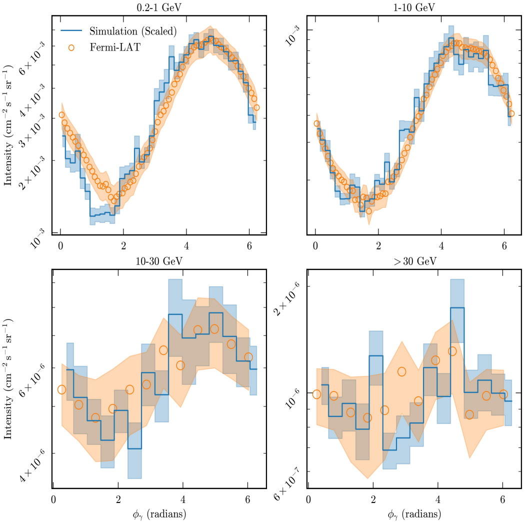
East-West Effect

North	$0^\circ < \phi_\gamma < 45^\circ \quad 315^\circ < \phi_\gamma < 360^\circ$
East	$45^\circ < \phi_\gamma < 135^\circ$
South	$135^\circ < \phi_\gamma < 225^\circ$
West	$225^\circ < \phi_\gamma < 315^\circ$

- γ-rays selected from the $60^\circ < \theta_\gamma < 75^\circ$ range
- Simulated intensities are scaled:

0.2-1 GeV	1-10 GeV	10-30 GeV	>30 GeV
1.19	1.23	1.14	1.58

- General agreement in shape with observed data

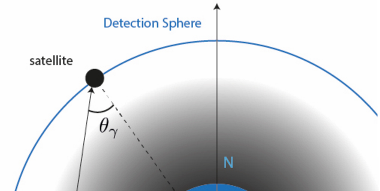


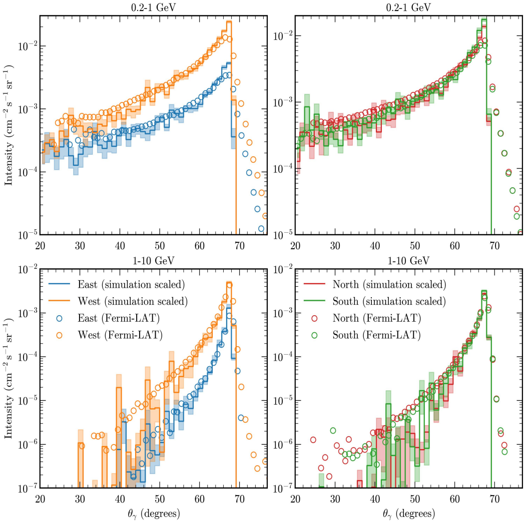
Nadir Angle Distribution

- Simulated intensities are scaled:

0.2-1 GeV	1-10 GeV
1.35	1.14

- General agreement in shape
- The observed distribution is slightly smeared due to the Fermi-LAT's point spread function





Conclusion

- Developed a simulation for Earth's atmospheric γ-rays.
- The simulation successfully reproduces energy spectra and angular distributions that match observations fairly well
- A discrepancy of $25 - 50\%$ remains in the overall normalization
- Future Work:
  1. Use the simulation to investigate the relationship between γ-ray intensity and proton cutoff rigidity, as observed in Madlee et al., 2020.
  2. Extend the study to other secondary particles (e.g., neutrinos, neutrons).

Acknowledgement

The works of the CUHK group are supported by the Croucher Foundation, RGC grants (24302721, 14305822, 14308023), the NSFC/RGC joint research scheme (N CUHK456/22), NSFC grant 12322517, and various CUHK internal grants.

References I

Abdo, A. A. et al. (Dec. 2009). "Fermi large area telescope observations of the cosmic-ray induced γ-ray emission of the Earth's atmosphere". In: 80.12, 122004, p. 122004. DOI: 10.1103/PhysRevD.80.122004. arXiv: 0912.1868 [astro-ph.HE].

Allison, J. et al. (2016). "Recent developments in Geant4". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 835, pp. 186–225. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2016.06.125.

Atwood, W. B. et al. (June 2009). In: 697.2, pp. 1071–1102. DOI: 10.1088/0004-637X/697/2/1071. arXiv: 0902.1089 [astro-ph.IM].

Emmert, J. T. et al. (2021). "NRLMSIS 2.0: A Whole-Atmosphere Empirical Model of Temperature and Neutral Species Densities". In: *Earth and Space Science* 8.3. e2020EA001321 2020EA001321, e2020EA001321. DOI: https://doi.org/10.1029/2020EA001321.

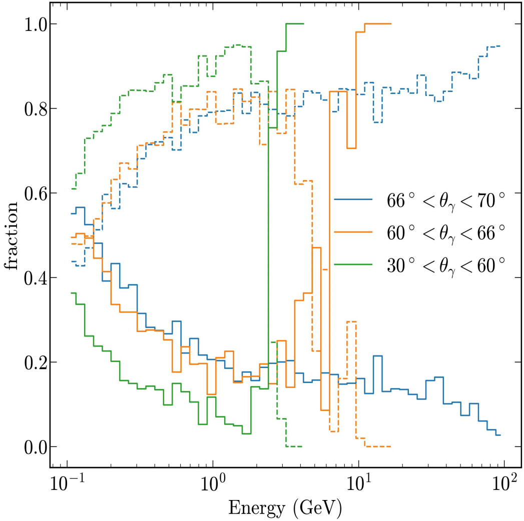
International Association of Geomagnetism and Aeronomy (Nov. 2024). *IGRF-14*. DOI: 10.5281/zenodo.14218973. URL: https://doi.org/10.5281/zenodo.14218973.

Madlee, S. et al. (2020). "First Analysis of Earth's Stratospheric -Ray Emission in Geographical Coordinates With Fermi LAT". In: *Journal of Geophysical Research: Space Physics* 125.9. e2020JA028151 10.1029/2020JA028151, e2020JA028151. DOI: https://doi.org/10.1029/2020JA028151.

Tsyganenko, N. A. and V. A. Andreeva (2016). "An empirical RBF model of the magnetosphere parameterized by interplanetary and ground-based drivers". In: *Journal of Geophysical Research: Space Physics* 121.11, pp. 10, 786–10, 802. DOI: https://doi.org/10.1002/2016JA023217.

Production Mechanism

- **Dashed lines:** Decay processes
- **Solid lines:** Bremsstrahlung radiation



Geographical Distribution of γ-intensity

- γ-rays selected at:
  - 565 km altitude
  - $60^\circ < \theta_\gamma < 75^\circ$

North	$0^\circ < \phi_\gamma < 45^\circ$ $315^\circ < \phi_\gamma < 360^\circ$
East	$45^\circ < \phi_\gamma < 135^\circ$
South	$135^\circ < \phi_\gamma < 225^\circ$
West	$225^\circ < \phi_\gamma < 315^\circ$