ShowerModel: A Python package for modelling cosmic-ray showers, their light production and their detection

Daniel Morcuende, and Jaime Rosado

IPARCOS and Department of EMFTEL, Universidad Complutense de Madrid, E-28040 Madrid, Spain; dmorcuen@ucm.es, jrosadov@ucm.es

Abstract. Cosmic-ray observatories necessarily rely on Monte Carlo simulations for their design, calibration and analysis of their data. Detailed simulations are very demanding computationally. We present a python-based package called ShowerModel to model cosmic-ray showers, their light production and their detection by an array of telescopes. It is based on parameterizations of both Cherenkov and fluorescence emission in cosmic-ray induced air showers. The package permits the modelling of fluorescence telescopes, imaging air Cherenkov telescopes, wide-angle Cherenkov detectors or any hybrid design.

ShowerModel was conceived as a tool to speed up calculations that do not require a full simulation or that may serve to complement complex Monte Carlo studies and data analyses (e.g., as a cross-check). It can also be used for educational purposes.

1. Introduction

Very-high-energy cosmic rays and gamma rays induce extensive air showers (EAS) when entering the atmosphere. Cherenkov and fluorescence light emitted by secondary charged particles is used as a proxy for studying the primary particles that initiate the particle cascades.

Design, calibration and data analysis of cosmic-ray and gamma-ray observatories strongly rely on Monte Carlo simulations of both the air shower and detector response. CORSIKA program (Heck et al. 1998) is widely used for carrying out the first step of the simulation, whereas the second step depends on the detection technique. For example, in the case of imaging atmospheric Cherenkov telescopes (IACT), the program sim_telarray (Bernlöhr 2008) is commonly used. These detailed simulations are currently very demanding computationally.

We present a fast python package called ShowerModel to compute the light emission in air showers and its detection by an array of telescopes (Morcuende & Rosado 2020). This tool can speed up calculations that do not require a full simulation or that may serve to complement complex Monte Carlo studies and data analyses (e.g., as a cross-check). It can also be used for educational purposes. A similar approach was presented previously in Vuillaume et al. (2017).

Functionalities and examples of results obtained with ShowerModel are shown. Several possible remarkable applications of this software are also briefly discussed.
2. ShowerModel

The package comprised several functions and classes to model air-shower development and detection (see Figure 1). Both gamma and proton-like 1D air showers can be generated using analytical Greisen or Gaisser-Hillas formulas (Greisen 1956; Gaisser & Hillas 1977). Simulation-generated longitudinal profiles can also be input. Different flat atmospheric models are available.

![Figure 1. Class dependency of ShowerModel.](image)

The code uses detailed parameterizations of both fluorescence and Cherenkov light emission and angular distribution (Morcuende et al. 2019; Nerling et al. 2006). The time-varying light intensity reaching a telescope is readily computed from geometry. Rayleigh scattering losses are also included.

Telescope objects are highly configurable (e.g., quantum efficiency, pointing direction, field of view, detection area) to model fluorescence telescopes, imaging air Cherenkov telescopes, wide-angle Cherenkov detectors or hybrid designs. Camera images are produced using the Nishimura-Kamata-Greisen (NKG) function (Kamata & Nishimura 1958; Greisen 1956) to describe the lateral distribution of electrons in the air shower.

3. Functionalities

ShowerModel permits the calculation of:

- Projection of shower tracks in local coordinates alt/az as well as the telescope field of view coordinates theta/phi (Figure 2, left).
- Longitudinal shower profiles: energy deposit and light production.
- Cherenkov and fluorescence photon densities on ground (Figure 3).
- Time evolution of signal in a telescope (Figure 2, right).
- Shower events detected by an array of telescopes (Figure 4).
- Camera images in customized telescopes (Figure 5).
4. Possible remarkable use cases

The proposed tool can serve as a complement of the analysis pipeline of cosmic-ray observatories. For instance, it might be used to fast evaluate if changes in the observation conditions (e.g., atmospheric parameters and night sky background) make necessary new simulations or instrument response functions. In addition, it may be useful to explore new observatory configurations or detection techniques that exploit both Cherenkov and fluorescence signals (see Contreras et al. (2016) and Sailer (2020)).
Figure 5. Camera images of an air shower observed by an array of six IACTs.

Acknowledgments. We gratefully acknowledge support from Spanish MINECO (contract FPA2017-82729-C6-3-R) and the European Commission (E.U. Grant Agreement 653477). D. Morcuende acknowledges a predoctoral grant UCM-Harvard University (CT17/17-CT18/17) from Universidad Complutense de Madrid.

References

Bernlöhr, K. 2008, Astropart. Phys., 30, 149. 0808.2253, URL https://doi.org/10.1016/j.astropartphys.2008.07.009

Contreras, J. L., Rosado, J., Arqueros, F., López, M., Barrio, J. A., & Nievas, M. 2016, PoS, ICRC2015, 993. URL https://doi.org/10.22323/1.236.0993

Gaisser, T. K., & Hillas, A. M. 1977, in International Cosmic Ray Conference, vol. 8 of International Cosmic Ray Conference, 353. URL https://ui.adsabs.harvard.edu/abs/1977ICRC....8..353G

Greisen, K. 1956, JG Wilson, Amsterdam, Netherlands, 3

Heck, D., Knapp, J., Capdevielle, J. N., Schatz, G., & Thouw, T. 1998, Forschungszentrum Karlsruhe, FZKA 6019, 1

Kamata, K., & Nishimura, J. 1958, Progress of Theoretical Physics Supplement, 6, 93. URL https://doi.org/10.1143/PTPS.6.93

Morcuende, D., & Rosado, J. 2020, JaimeRosado/ShowerModel v0.1.4. URL https://github.com/JaimeRosado/ShowerModel

Morcuende, D., Rosado, J., Contreras, J., & Arqueros, F. 2019, Astroparticle Physics, 107, 26. URL https://doi.org/10.1016/j.astropartphys.2018.11.003

Nerling, F., Blümer, J., Engel, R., & Risse, M. 2006, Astropart. Phys., 24, 421. URL https://doi.org/10.1016/j.astropartphys.2005.09.002

Sailer, S. 2020, Ph.D. thesis, Heidelberg University, Combined Faculty of Natural Sciences and Mathematics, Germany. URL http://www.ub.uni-heidelberg.de/archiv/29105

Vuillaume, T., Gaté, F., Maurin, G., Jacquemier, J., & Lamanna, G. 2017, PoS, ICRC2017, 772. URL https://doi.org/10.22323/1.301.0772