CHASM (CHerenkov Air Shower Model): Simulating the Cherenkov Profiles of Cosmic Ray Air Showers

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Introduction

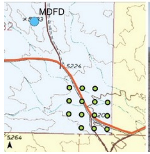
- This poster shows how shower universality can be used to simulate the Cherenkov light profile of cosmic ray air showers.
- The CHASM python module was developed for all shower geometries and profiles, and is intended to be a computationally efficient alternative to Monte Carlo air shower simulation packages like CORSIKA.
- CHASM is still in development. This poster is meant to showcase its current progress and functionality.
- This poster includes simulations of Cherenkov distributions from various shower types, as well as comparisons to CORSIKA's IACT (Imaging Atmospheric Cherenkov Telescope) extension.

What is Shower Universality?

- Shower universality is the principle that properties of secondary particles in an air shower such as propagation direction, energy, and lateral spread can be represented by universal parameterized distributions [1, 2].
- These parameterizations vary as a shower develops and take into account secondary particle properties such as energy (i.e. the directional distribution of particles in a given energy interval will be narrower for higher energies).
- Charged particles in a shower will produce Cherenkov light in a cone determined by particle energy and the atmospheric index of refraction in which they propagate.
- Published fits to secondary particle distributions were used to create a table of Cherenkov angular distributions at various atmospheric indices of refraction and stages of shower development.
- CHASM generates a shower profile in the Earth's atmosphere, then accesses the Cherenkov table to calculate the photon yield at user defined locations.

NICHE (Non Imaging CHErenkov) and TALE (Telescope Array Low Energy)

An efficient Cherenkov signal simulation will enable a hybrid analysis of the low-energy cosmic ray spectrum using data from both the TALE fluorescence detector and the NICHE detectors near the Middle Drum telescope site.



The array of NICHE counters

One of the counters with Middle Drum in the Background

References:
[1] S. Lafebre, et al., Astropart. Phys. 31 (2009) 243.
[2] M. Giller, et al., J. Phys. G 30 (2004) 97.
[3] J. Krizmanic, et al., PoS(ICRC2019)936.

Acknowledgements:
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Universality vs. CORSIKA

- To demonstrate the veracity of the Cherenkov universality model, we generated a Cherenkov light profile using universality, and compared it to a profile generated by CORSIKA's IACT extension.
- This downward proton shower has a primary energy of 10^8 GeV, X_{max} at 863 g/cm², N_{max} of ~67 million particles, and a polar angle of 10 degrees.
- X_{max} and N_{max} refer to the atmospheric depth at shower maximum and the maximum number of secondary shower particles, respectively.
- IACT counters were defined at the altitude of the lowest Telescope Array NICHE counter (1564 m above sea level).

The total number of photons collected at increasing distances from the shower core are shown in Figure 1, and the arrival time distributions are compared for a counter 70 m from the shower core in Figure 2.

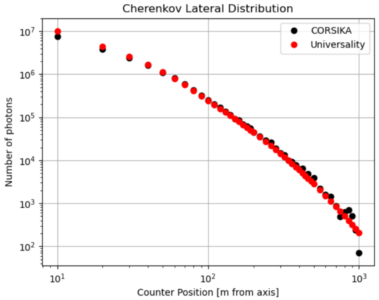

Figure 1: Comparison of Cherenkov lateral distribution from both CORSIKA and universality.

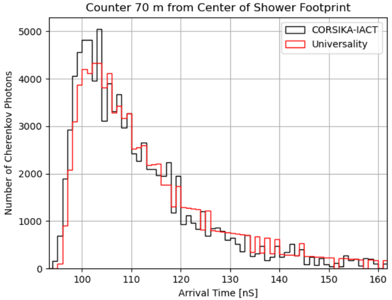

Figure 2: Comparison of arrival time distribution from both CORSIKA and universality.

Hypothetical Tau Primary Upward Air Shower

- The first iteration of this package is being tested for implementation in nuSpaceSim, a comprehensive neutrino simulation package for space-based & suborbital experiments [3].
- Tau neutrinos skimming the Earth may interact via the charged-current interaction in the Earth's crust. The resulting tau particle leaves the Earth and decays, serving as the primary particle in an upward going air shower.
- For this demo, an upward shower profile was generated using the Gaisser-Hillas function with an X_{max} of 785 g/cm², an N_{max} of 80 million particles, and a first-interaction height of 10 Km.
- The resulting Cherenkov light was calculated at an array of locations normal to the shower axis at an altitude of 525 km.

The diagram below shows the shower orientation, as well as the x and z axes of the coordinate system used by CHASM. The origin is where the shower axis intersects with the Earth's surface. Standard physics spherical coordinate conventions apply for the shower polar angle.

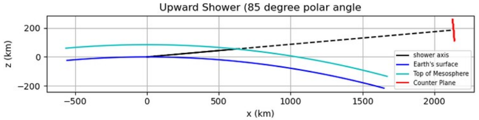

Figure 3: Diagram of an upward air shower axis showing the orientation of an orbital counter array.

Below is a plot of the Cherenkov signal at the counter plane. Each pixel represents one photon counter location. The ring where the maximum signal is found forms due to the shower's Cherenkov cone at development stages near X-max.

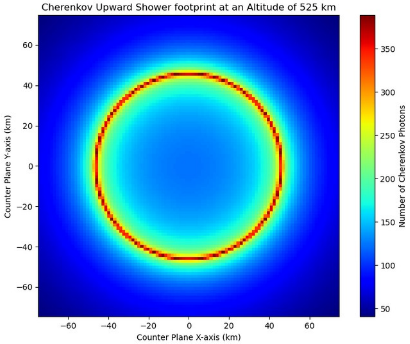

Figure 4: Cherenkov light signal at an orbital counter array normal to the shower axis at an altitude of 525 km.

Atmospheric Curvature and Photon Timing

- As photons propagate in the atmosphere to the counting location, they are delayed compared to the speed of light in a vacuum.
- For downward showers, it is sufficient to divide the delay a vertically traveling photon would experience by the cosine of its polar angle.
- In the context of orbital observations (nuSpaceSim), photons propagate for thousands of kilometers in the upper atmosphere before they enter the vacuum of space.
- As the photons get higher, their angle of propagation with respect to the atmosphere becomes steeper compared to their polar angle with respect to the original z-axis.

This difference was calculated as a function of atmospheric height via the law of cosines on the inscribed triangle in Figure 5 below.

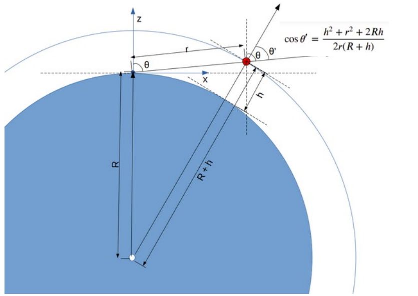

Figure 5: Diagram of the geometry used to account for the curvature of the atmosphere in upward shower timing calculations.

For the upward shower shown in Figures 3 and 4, there is about a seven nanosecond delay if the curvature of the atmosphere is neglected. Figure 6 shows the both the original and corrected arrival time distribution at one of the counters in the ring peak.

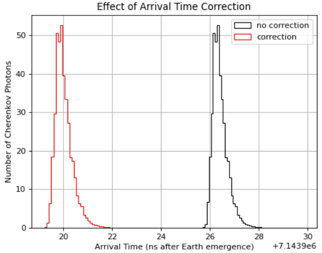

Figure 6: Comparison of arrival time distribution when atmospheric curvature is neglected and accounted for.