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A new technique for probing the internal structure of volcanoes using cosmic-ray muons

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Abstract

Among the considerable number of studies that can be carried out using muons, we pay specific attention to the radiography of volcanoes based on the same principle of the X-ray radiography of human body. Thanks to their high penetration capability, cosmic-ray muons can be used to reconstruct the density distribution of the interior of huge structures by measuring the attenuation induced by the material on the muon flux. In particular, the quantitative understanding of the inner structure of volcanoes is a key-point to forecast the dangerous stages of activity and mitigate volcanic hazards. The instrumental approach is currently based on the detection of muons crossing hodoscopes made up of scintillator planes. Unfortunately, these detectors are affected by a strong background comprised by accidental coincidence of vertical shower particles, horizontal high-energy electrons and upward going particles. We propose an alternative technique based on the detection of the Cherenkov light produced by muons. This can be achieved with an imaging atmospheric Cherenkov telescope composed of a high reflectivity optical system that focus the Cherenkov light onto a multi-pixel focal camera with fast read-out electronics. The Cherenkov light emitted by a muon is imaged on the camera as an annular pattern which contains information to reconstruct the direction of the incident muon. We have estimated that using the Cherenkov imaging technique for muon radiography of volcanoes gives the advantage of a negligible background and improved spatial resolution, compared to the majority of the particle detectors. We present results of simulations based on a telescope with a positioning resolution of 13.5 m which corresponds to an acceptance of 9 cm^2 sr. The telescope is located 1500 m far from a toy-model volcano, namely, a cone with a base diameter of 500 m and a height of 240 m. We test the feasibility of the proposed method by estimating the minimum number of observation nights needed to resolve inner empty conduits of different diameter.

Keywords: Imaging Atmospheric Cherenkov Telescope, Volcano radiography, Muons, Volcano monitoring, Mount Etna

1. Introduction

Quantifying eruption hazards consists in answering the question: how is the present state of the volcano far from a destabilisation state? Collecting geological data provides information concerning the various destabilisation scenarios which occurred in the past and may happen again. Geological data also give insights on time scales and recurrence periods for the different classes of events in order to get estimates of their occurrence probabilities. The knowledge of the volcano interior, for instance measuring the size and the exact shape of the volcano conduits, the magma level, the obstructed conduits, constitutes a major issue to reach precise (as possible) characterisation of the present state of the volcano and determine its instantaneous evolution trajectory.

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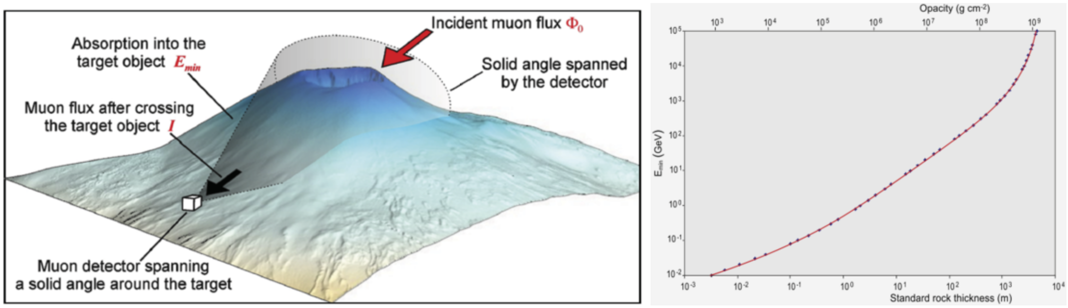

Figure 1: Sketch of the muon radiography principles (left, from [4]). Energy threshold for a muon to cross a length of rock of given density (right).

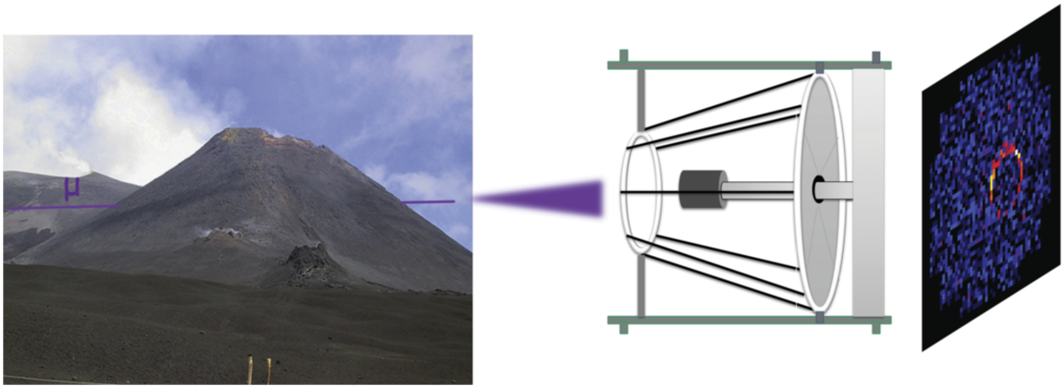

Figure 2: The South-East crater of Mt Etna and the sketch of our proposed instrument. The camera images the Cherenkov photons by a muon with a characteristic ring shape.

1.1. Principle of muon imaging of volcanoes

Thanks to their high penetration capability, cosmic-ray muons can travel through huge structures losing a fraction (up to the total) of energy proportionally to the thickness of the crossed material. In particular, by measuring the differential attenuation of the muon flux crossing a volcano, it can be determined the density distribution of its interior [1]. This is the principle of muon radiography which is a promising technique to study the inner structure of volcanoes ([2] and reference therein). Tanaka et al. [3] observed the presence of low-density regions inside the Asama volcano which can be used in computer simulations that predict how possible eruptions could develop, indicating the most dangerous areas around the volcano. Their observations showed that muon radiography could produce useful images of the internal structure of volcanoes.

The minimum initial energy (E_{min}) needed by a muon to cross a length of rock of a given density (Fig. 1, right), is determined from the energy loss of muons across rock and is used to compute the theoretical integrated muon flux, I, after the target has been crossed (see Fig. 1, left, from [4]), starting from the model of the differential incident flux (Φ_0; [5]). Lesparre et al. [5] defined a relation linking the muon flux I, the acquisition time ΔT, the amount of crossed matter (opacity, ϵ) and the telescope acceptance Γ (this latter depends on the telescope geometric area and on the angular resolution). The following equation represents the feasibility condition:

$$\Delta T \times \Gamma \times \frac{\Delta I^2(\epsilon_0, \delta\epsilon)}{I(\epsilon_0)} > 1 \qquad (1)$$

The left-hand term of the condition is determined by the fixed total opacity of the medium (ϵ_0) and by the desired resolution level ($\delta\epsilon$). This equation establishes a useful condition to evaluate the acquisition time ΔT necessary to collect a statistically significant (1σ) number of muons to resolve the target with a resolution level $\delta\epsilon$.

1.2. Current Experiments

Up to now, measurements of the inner structure of volcanoes using muons have been based on the detection of muon-track crossing hodoscopes made up of scintillators or nuclear emulsion planes [6, 7, 4]. However, this technique requires several detection layers and