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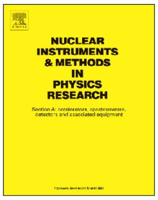

Volcanoes muon imaging using Cherenkov telescopes

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ABSTRACT

A detailed understanding of a volcano inner structure is one of the key-points for the volcanic hazards evaluation. To this aim, in the last decade, geophysical radiography techniques using cosmic muon particles have been proposed. By measuring the differential attenuation of the muon flux as a function of the amount of rock crossed along different directions, it is possible to determine the density distribution of the interior of a volcano. Up to now, a number of experiments have been based on the detection of the muon tracks crossing hodoscopes, made up of scintillators or nuclear emulsion planes.

Using telescopes based on the atmospheric Cherenkov imaging technique, we propose a new approach to study the interior of volcanoes detecting of the Cherenkov light produced by relativistic cosmic-ray muons that survive after crossing the volcano. The Cherenkov light produced along the muon path is imaged as a typical annular pattern containing all the essential information to reconstruct particle direction and energy. Our new approach offers the advantage of a negligible background and an improved spatial resolution.

To test the feasibility of our new method, we have carried out simulations with a toy-model based on the geometrical parameters of ASTRI SST-2M, i.e. the imaging atmospheric Cherenkov telescope currently under installation onto the Etna volcano. Comparing the results of our simulations with previous experiments based on particle detectors, we gain at least a factor of 10 in sensitivity. The result of this study shows that we resolve an empty cylinder with a radius of about 100 m located inside a volcano in less than 4 days, which implies a limit on the magma velocity of 5 m/h.

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1. Introduction

Cosmic ray muons are created when high energy primary cosmic rays interact with the Earth' s atmosphere (see [1] for a recent review). Muon imaging for non-destructive studies of gigantic objects arose soon after their discovery. Muon radiography was first proposed to determine the thickness of a snow horizontal tunnel on a mountain in Australia [2]. Then, in archeology, it was adopted to investigate the interior of the Egyptian pyramid of Chephren at Giza in order to find a hidden chamber [3]. Very recently the muon tomography technique has been used to inspect the content of traveling cargo containers [4]. In 2007, H. Tanaka and collaborators from the University of Tokyo were the first to apply this technique to volcanoes [10].

Volcanic eruptions occur when magma from the inner of the Earth comes out on the surface through the main conduit or conduits connecting the underground magma reservoir with the erupting crater. The eruptions come out from the volcano's mouth or from a number of mouths that open at different points. The duration of volcanic eruptions is variable: they may last a few hours or even decades. Although the interpretation of geophysical signals emitted from volcanic conduits such as micro-seismicity, surface deformation and gas and thermal emissions are used for eruption forecasts, only little direct information is available on the conditions inside and near the conduit of an active volcano. Improvements in measuring the size of the conduits could help in the interpretation of premonitory marks and in the risk reduction.

The density distribution of the interior of a volcano has been determined by measuring the differential attenuation of the muon flux as a function of the amount of rock crossed along different directions. So far, measurements in this context have been based on the detection of the muon tracks crossing hodoscopes, made up of scintillators or nuclear emulsion planes. However, this technique requires several detection layers and a sufficiently high timing resolution to reduce the level of fake coincidences due to the unavoidable charged particles background.

We present for the first time the feasibility study of using an imaging Cherenkov telescope to carry out the muon radiography of a volcano. We aim to apply this technique to the Etna volcano using the ASTRI SST-2M telescope currently under installation. The

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advantage of using Cherenkov telescopes for muon radiography is due to their imaging capability which results in negligible background and improved spatial resolution compared to the traditional particle detectors.

2. Muon radiography: observational approach

Muon imaging allows us to determine the density variations in the inner structure of a volcano by measuring the differential attenuation of the muon flux.

2.1. Principles of muon imaging

The flux of atmospheric muons incoming the volcano at a given arrival direction can be determined using Monte Carlo simulation codes [5] or fitting data of experimental results obtained looking at the open sky at the same angle [6].

Any muon flux variation translates in a difference in the opacity (X) which is defined as:

$$X(L) \equiv \int_L \rho(\xi)\,\mathrm{d}\xi\ (\mathrm{g\ cm^{-2}}) \tag{1}$$

where ρ is the rock density and ξ is the spatial coordinate measured along the trajectory L of the muon crossing the rock.

The integrated cosmic muon flux after the volcano has been crossed (as a function of the opacity X and of the zenith angle θ) is defined as:

$$I(X,\theta) = \int_{E_{\min}}^{\infty} J(E,\theta)\,\mathrm{d}E\ (\mathrm{cm^{-2}\ sr^{-1}\ day^{-1}}). \tag{2}$$

where $J(E,\theta) \equiv \mathrm{d}N(E,\theta)/\mathrm{d}E$ ($\mathrm{cm^{-2}\ sr^{-1}\ day^{-1}\ GeV^{-1}}$) is the differential flux of incident muons at a given angle. The minimum muon energy ($E_{\min}$) required to cross a depth of opacity X is calculated using the classical definition of the average muon energy loss:

$$\mathrm{d}E_\mu/\mathrm{d}X = -a - bE_\mu \tag{3}$$

with $a \approx 2$ MeV $\mathrm{g^{-1}\ cm^2}$ and $b \approx 4 \times 10^{-6}\ \mathrm{g^{-1}\ cm^2}$ [7] for a rock with standard density (2.65 $\mathrm{g\ cm^{-3}}$). Using Eq. (3), the muon energy after propagation is:

$$E_\mu = (E_\mu^0 + \epsilon)\exp(-bX) - \epsilon \tag{4}$$

with $\epsilon = a/b$ and E_μ^0 the energy of the incident muon. Resolving Eq. (4) for $E_\mu = 0$, we obtain the minimum muon energy required to cross a depth with opacity X:

$$E_{\min} = \epsilon\ [\exp(+bX) - 1]. \tag{5}$$

Fig. 1 shows the minimum muon energy corresponding to the propagation path in a standard density rock.

The feasibility of the muon imaging to investigate the density distribution inside a target structure can be inferred through the relation suggested and exhaustively treated in [8] :

$$\Delta T \times \Gamma \times \frac{\Delta I^2(X_0,\delta X)}{I(X_0)} > 1 \tag{6}$$

with ΔT being the acquisition time, $\Delta I(X_0,\delta X) = I(X_0+\delta X) - I(X_0)$, X_0 the fixed total opacity of the medium, δX the required resolution level, and Γ the detector acceptance defined as:

$$\Gamma = A \times 2\pi(1 - \cos(\alpha/2)) \tag{7}$$

where A is the detector geometrical area and α is the angular resolution. Density and size of the volcano inner structure can be estimated with an angular resolution driven by the detector performance.

Eq. (6) establishes a useful relationship between the acquisition time necessary to collect a statistically significant number of muons, ΔT, and the integrated flux differences of muons crossing different directions inside the target, $\Delta I(X_0,\delta X) = I(X_0+\delta X) - I(X_0)$. It is worth noting that Eq. (6) is applicable only in case of negligible background.

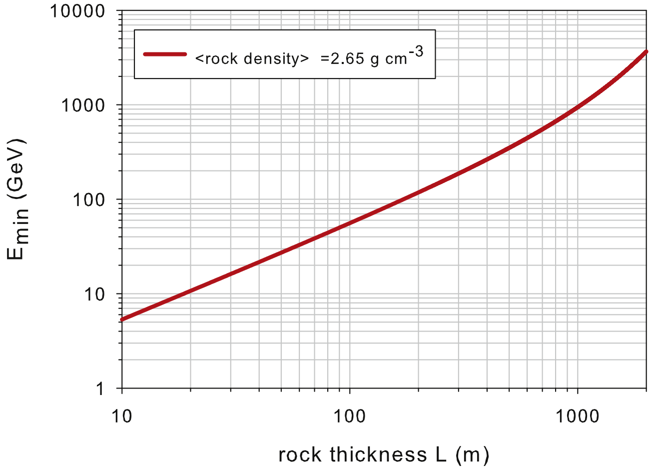

Fig. 1. Energy threshold for a muon to cross a rock with standard density (2.65 $\mathrm{g\ cm^{-3}}$) at different thicknesses. The curve results from Eq. (5).

2.2. Experiments

The instrumental approach is currently based on the detection of muons crossing hodoscopes made up of scintillator planes. First results have been obtained by Tanaka and collaborators who carried out muon radiography of the top part of the Asama volcano in Japan and revealed a region with rock of low density on the bottom of the crater [10,11]. They definitely demonstrated the feasibility of the method to detect both spatial and temporal changes of density inside a volcano [12–14]. Very recently, the first muographic visualisation of the dynamics of a magma column in an erupting volcano has been presented [15]. These authors performed a muon radiography of the Satsuma–Iwojima volcano showing that while the eruption column was observed, the top of the magma column reached a location of 60 m beneath the crater floor. Moreover, they proposed that the monitoring of the temporal variations in the gas volume of the magma as well as its position in a conduit could be used to support eruption prediction. Recently, a new telescope prototype has been proposed to study Mt. Vesuvius [16]. It is based on the use of bars of plastic scintillator with a triangular section whose scintillation light is collected by Wave-Length Shifting (WLS) optical fibers and transported to Silicon photomultipliers [17].

In the summer 2010, the first experiment of muon radiography at Mt. Etna by using a detector employing two scintillator planes was carried out [18]. A marked difference between theoretical and observed attenuation of muons through the crater was found. This discrepancy was likely due to the bias on the observed flux, arising from false muon tracks. These are caused by muons arriving from isotropic directions and by low-energy particles of ordinary air showers that, by chance, hit simultaneously the two detector planes, leading to the detection of a false positive.

3. Muons with Cherenkov telescopes

Cherenkov light is emitted when charged particles, such as muons, travel through a dielectric medium with velocity (v) higher than the speed of light in that medium, i.e. $v > c/n$ where c is the speed of light in vacuum and n the refraction index. This implies an energy threshold for Cherenkov production of ~ 5 GeV in the

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