Volcanoes muon imaging using the ASTRI Cherenkov prototype

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on behalf of the ASTRI Collaboration
The majestic Etna volcano rises at North-Est of the Serra La Nave Observatory where the ASTRI SST-2M telescope is located.
Muons crossing the SE volcano crater
Muon Cherenkov ring

**THE INTUITION - MUONS**

Muons are produced in the earth atmosphere when pions are created in the interaction of primary cosmic rays (e.g. protons) with the nuclei of the air up there. Those pions decay into muons and their antineutrinos.

As muons interact very little with matter they can travel through a large extent of rocks, losing a fraction of energy proportionally to the thickness of the rocks crossed. Density distribution of the interior of a volcano can be determined by measuring the differential attenuation of the muon flux as a function of the amount of rocks crossed along different directions.

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Can be measured the width, structure and shape of volcano conduit??

Improvements in measuring conduits could help in the interpretation of premonitory marks and consequently risk reduction for property and people during eruptions.
DIAPHANE project
MURAY project

Measurements of the inner structure of volcanos using muons are based on the detection of muons-track crossing hodoscopes made up of scintillators or nuclear emulsion planes.

HIGH BACKGROUND RATE
(FALSE POSITIVE)
Muon detection by Cherenkov Telescope. Muons create typical annular patterns in the multi-pixels camera placed at the focus of the converging optics of the telescope.

Figure 3.79: Ground level measurement of upward directed atmospheric muons of energy ≥4 GeV resulting from backscattering in the ground compared with a prediction. The horizontal telescope had an area of 2 m² and a horizontal depth of 11.07 m. (Abbrescia et al. (1993)).

NO BACKGROUND
Muons with Cherenkov Telescopes

Muon ring analysis is a powerful and precise method to calibrate the optical throughput of Cherenkov Telescopes.

- The radius of the ring corresponds to the Cherenkov angle $\Theta$
- $E_\mu$ is given by:

$$E_\mu = \frac{0.105}{\sqrt{1 - (n \cos \Theta)^{-2}}} \text{ (GeV)}$$

- The position of the center gives the direction of the detected muon with respect to the telescope optics axis.

The amount of collected light mainly depends on the impact point of the muon on the telescope mirror, on the telescope entrance pupil area and on the camera efficiency.

The ASTRI SST-2M telescope is able to reconstruct muons with energy higher than 20 GeV with a precision on the direction reconstruction of about $0.14^\circ$, which is of the same order of the camera pixel.
The density distribution of the interior of a volcano can be determined by measuring the differential attenuation of the muon flux as a function of the amount of rock crossed along different directions. Any muon flux variation translates in a difference in the opacity $(X)$ which is defined as:

$$X(L) \equiv \int_{L} \rho(\xi) \, d\xi \, (\text{g cm}^{-2})$$

where $\rho$ is the density and $\xi$ is the spatial coordinate measured along the trajectory $L$. 
Principles of muon imaging

The integrated cosmic muon flux after the volcano has been crossed, as a function of the opacity and of the zenith angle $\theta$, is defined as:

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

With $J(E, \theta) \equiv dN(E, \theta)/dE \, (\text{cm}^{-2} \, \text{sr}^{-1} \, \text{day}^{-1} \, \text{GeV}^{-1})$ the differential flux of incident muons.

The minimum muon energy required to cross a depth $X$:

$$E_{\text{min}} = \epsilon [\exp(+bX) - 1]$$
**Principles of muon imaging**

Muon integrated flux as a function of the standard rock thickness (2.65 g cm\(^{-3}\)). The top axis gives the required minimum energy to cross the corresponding rock thickness.

The feasibility of the method proposed to investigate the density distribution inside a target structure can be inferred through the relation:

\[
\Delta T \times \Gamma \times \frac{\Delta I(X_0, \delta X)^2}{I(X_0)} > 1
\]

with \(\Delta T\) the acquisition time, \(\Delta I(X_0, \delta X) = I(X_0 + \delta X) - I(X_0)\) and \(\Gamma\) the detector acceptance.

This equation establishes a useful relationship between the acquisition time \(\Delta T\) necessary to collect a statistically significant number of muons and the integrated flux differences \(\Delta I(X_0, \delta X) = I(X_0 + \delta X) - I(X_0)\) of muons crossing different directions inside the target.
Conduits of various dimensions are simulated as hollow cylinders embedded into a filled cone with the vertical axis coincident with that of the cone (volcano).

Angular Resolution $\approx 0.5$ degrees

Projected Spatial Resolution $\approx 14$ m

A grid with bins of 0.5° x 0.5° maps the crater

Bin detector acceptance $\approx 10$ cm$^2$ sr

Differential muon flux ($I(X, \theta$ for $\theta = 85^\circ$) calculated for standard rock ($\rho = 2.65$ g cm$^{-3}$) and propagated

+ RECEIPTION FLUCTUATION
SIMULATIONS

No Conduit: Muon Flux per bin

200 m Conduit: Muon Flux per bin

Opacity Resolving Time

Max Hours = 6.00

Resolving Time (hours) @ 1.0 σ

Height

Volcano sliced

(bin = 13.5 m)

500 m

240 m
SIMULATIONS

LONG TERM OBSERVATION
Increasing observation time

Higher confidence level in opacity measurement and detailed map of the interior of the volcano within the limit of the telescope resolution.

SHORT TERM OBSERVATION
Capability to detect the rising magma in the conduit

200 m conduit resolvable if \( <v> \) magma < 5m/h
Multidirectional radiography (tomography) can resolve the exact position of the density anomaly, its shape and its alignment by superimposing images obtained by each telescope and producing three dimensional images of the region of interest.

Additional telescopes installed on mobile vehicles and solar powered. Such Cherenkov telescopes do not need to be ASTRI-like and do not need a pointing system or a double mirror.
YOU KNOW THAT…..

About 1300 active volcanos in the WORLD

Japan has one of the largest volcanologic activity in the world

Mount Asama, H.T.M. Tanaka et al: pionneering works from the Tokyo group
THANKS

I am grateful to the entire ASTRI collaboration and to the INAF HQ for encouraging this work