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Looking inside volcanoes with the Imaging Atmospheric Cherenkov Telescopes

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ABSTRACT

Cherenkov light is emitted when charged particles travel through a dielectric medium with velocity higher than the speed of light in the medium. The ground-based Imaging Atmospheric Cherenkov Telescopes (IACT), dedicated to the very-high energy γ-ray Astrophysics, are based on the detection of the Cherenkov light produced by relativistic charged particles in a shower induced by TeV photons interacting with the Earth atmosphere. Usually, an IACT consists of a large segmented mirror which reflects the Cherenkov light onto an array of sensors, placed at the focal plane, equipped by fast electronics. Cherenkov light from muons is imaged by an IACT as a ring, when muon hits the mirror, or as an arc when the impact point is outside the mirror. The Cherenkov ring pattern contains information necessary to assess both direction and energy of the incident muon. Taking advantage of the muon detection capability of IACTs, we present a new application of the Cherenkov technique that can be used to perform the muon radiography of volcanoes. The quantitative understanding of the inner structure of a volcano is a key-point to monitor the stages of the volcano activity, to forecast the next eruptive style and, eventually, to mitigate volcanic hazards. Muon radiography shares the same principle as X-ray radiography: muons are attenuated by higher density regions inside the target so that, by measuring the differential attenuation of the muon flux along different directions, it is possible to determine the density distribution of the interior of a volcano. To date, muon imaging of volcanic structures has been mainly achieved with detectors made up of scintillator planes. The advantage of using Cherenkov telescopes is that they are negligibly affected by background noise and allow a consistently improved spatial resolution when compared to the majority of the current detectors.

1. Introduction

The internal structure of the upper part of a volcano edifice is of great interest. Indeed, the models describing the transport of magma to the surface require input data about size, shape and position of conduits and shallow accumulation zones. This information is thus important to model the underlying processes and better understand the state of activity of the studied volcano, and possibly forecast the nature of the next eruption. The geophysical techniques most commonly used to image the internal structure of a volcano do not provide adequate spatial resolution of the uppermost part of the edifice and may require measurements close to the active structures, implying a risk for the personnel involved. During the past decade, it has been shown the potential of cosmic-muon imaging as a tool for investigating the internal structure of a volcano safely and with high spatial resolution.

2. Muon radiography of volcanoes

The basic principle is the same as X-ray radiography. Muons interact with electrons and nucleons of the crossed matter and the number of interactions increases proportional to the density length, which results in the attenuation of the incident muon flux (Φ). By measuring the differential attenuation of the muon flux (I) along different directions, it is possible to determine the density distribution of the interior of a volcano (Fig. 1, left).

In particular, the basic idea can be explained through the following steps:

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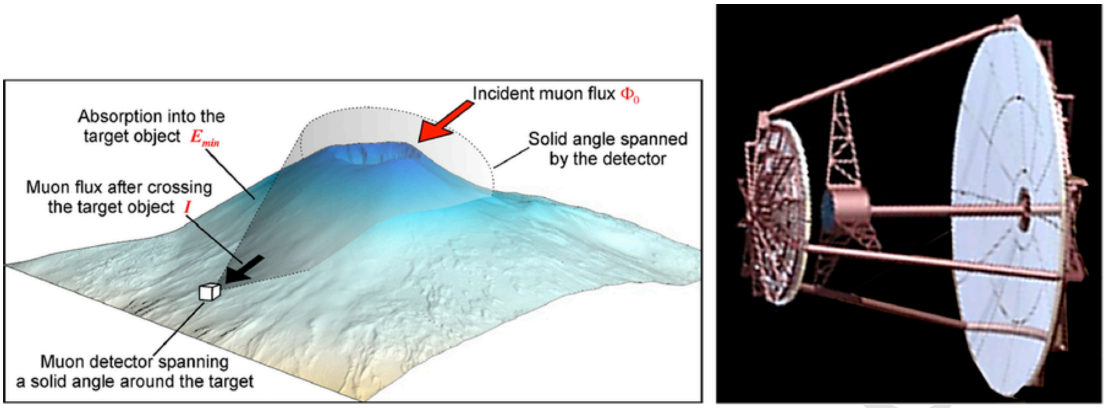

Fig. 1. Left: sketch of the muon radiography principles (from [6]). Right: schematic representation of a IACT with its main components. The primary mirror (right), optical camera (middle), secondary mirror (left) are shown.

- thanks to their high penetration capability, cosmic-ray muons can travel through km-size objects, losing a fraction, up to the total, of their energy;
- a unique relationship exists between the opacity of the crossed medium and the intensity of the penetrating cosmic-ray muons;
- the energy spectrum of cosmic-ray muons depends on the elevation angle.

Volcano imaging through cosmic-ray muons is a promising technique [1–3]. The experiment of muon radiography carried out at Mt. Asama volcano allowed the reconstruction of the density map of the cone and detection of a dense region that corresponds to the position and shape of a lava dome created during the 2004 and 2009 eruptions [2,4]. A first radiographic observation of the ascent and descent of magma along a conduit of the Satsuma-Iwojima volcano has been performed using muography with dynamic radiographic imaging [5].

2.1. Muon-radiography at Etna volcano

Mt. Etna is a large volcano located on the East coast of Sicily (Italy). It has a base diameter of about 40 km and a height of about 3.4 km. In order to have a sufficient flux to perform muon imaging, the thickness of rock to be crossed by muons should not exceed a few kilometres, so that only a small portion of this volcano can be investigated through this technique. One of the active craters, i.e. the South East Crater (SEC), has been chosen as a target for the first experiment of muon radiography at Mt. Etna [6,7]. The height and base diameter of this crater are about 240 m and 500 m, respectively. The detector was made by plastic scintillator strips, organised in two series of rows and columns, to form two matrix planes. Carbone et al. [6] found a strong difference between synthetic and observed attenuation of muons through the target which was likely due to the bias on the observed flux, arising from false muon tracks. These are due to the low energy particles that, by chance, hit simultaneously the two detector layers. The strong background noise from false muon tracks made the data acquired at Etna not adequate to obtain quantitative information on the density distribution inside the SEC. However, qualitative understanding could be gained through the first-order noise model derived by these authors.

2.2. Current experiments

Up to now, particle detectors investigating the interior of volcanoes via muon radiography have been based on the detection of muon-tracks crossing hodoscopes made up of scintillators or nuclear emulsion planes (e.g. [8,9]). In position sensitive systems the major source of the fake muon tracks is the accidental coincidence of vertical electro-magnetic shower particles. The effect of these false muon tracks can be drastically reduced through the use of several detection planes. In addition, the background noise or the fake tracks triggered by horizontal high energy electrons and low energy muons can be reduced by inserting thick steel or lead shields in between the planes [5]. However, this configuration results in a very heavy and expensive instrument, as well as difficult to carry and install under the harsh conditions of volcanic environments.

3. Muography with IACT

A new window to the ground-based γ-ray astronomy has been opened by Imaging Atmospheric Cherenkov Telescope (IACT) in the last years [10–12]. Basically, an IACT consists of an optical system formed by highly reflectivity mirror(s) that focusses the impinging Cherenkov radiation onto a multi-pixel camera. The latter is equipped with a fast read-out electronics (Fig. 1, right). The next generation of IACTs is the Cherenkov Telescope Array (CTA; [13]) which will provide a deep insight into the non-thermal high-energy Universe. An end-to-end prototype, ASTRI SST-2 M (hereafter ASTRI [14]), proposed for the small-sized telescopes (>2 TeV) of the CTA has been realised by the Italian National Institute of Astrophysics (INAF). ASTRI has been installed on the slopes of Mt. Etna at the INAF "M.C. Fracastoro" observing station [15] located in Serra La Nave (1750 m a.s.l.). The telescope is equipped with two mirrors in the Schwarzschild-Couder configuration [16] and a small size camera made up of 37 photon detection modules of 8×8 Silicon Photo-Multiplier (SiPM) pixels [17]. Muons hitting the mirror create typical annular patterns onto the multi-pixels camera placed at the focus of the telescope (see e.g. Fig. 2). A relatively simple geometrical analysis of the ring allows the reconstruction of the muon physical parameters, such as the energy (up to a saturation level) and the arrival direction. In particular, the latter is necessary for muography studies. The capability to reconstruct muon rings depends on the impact point on the telescope mirror, on the telescope entrance pupil area and on the camera efficiency. ASTRI is able to reconstruct muons with energy higher than 20 GeV with a precision on the direction reconstruction of about 0.14° [18].

We propose a new approach starting from the following question: is the muon radiography feasible with an IACT?

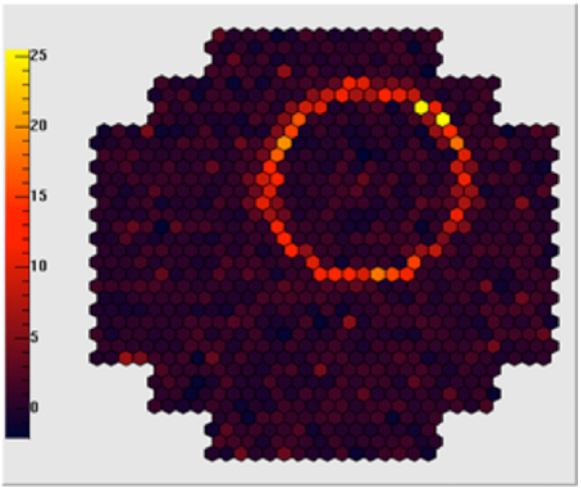

Fig. 2. Muon ring images with a Cherenkov telescope (H.E.S.S. in this case) when muon hits the mirror.

3.1. Simulations

In order to estimate the feasibility of an IACT to perform the muon radiography of one of Mt. Etna's craters, we performed simulations based on a toy-model of the volcano crater and internal conduits, i.e. a simple cone with base diameter and height of 500 and 240 m, respectively and hollow cylinders of various diameters along the axis of the cone. As telescope, we assumed ASTRI, covering a 9.6° field of view (FOV), positioned at 1.5 km (hereafter ASTRI-like, see Fig. 3, left.) far from the SEC (instead of the real 5 km distance): in doing that, we had the whole cone in the FOV. The angular resolution of such a system is 0.5° corresponding to a projected spatial resolution of 13.5 m. This pixel size is comparable to the muon angular deviation expected from multiple scattering in crossing the mountain [19]. The synthetic integrated muon flux has been computed by Lesparre et al. [7] for standard rock density (2.65 g cm^{-3}) and for an elevation angle of 85°.

Results have been reported and extensively discussed in Catalano et al. [20]. In this contribution, we show the simulation assuming a hollow cylinder with diameter of 100 m, inside the toy model (Fig. 3, right): the whole empty conduit can be resolved in about 9 nights of observations (for an IACT we have on average 8 h observations per night).

3.2. Background

An IACT dedicated to the muon radiography is not affected by fake muons, neither by low energy muons (below 5 GeV they do not emit Cherenkov light). The only background expected is due to muons hitting the primary mirror with an incidence angle within the FOV and not emerging of the mountain, those are mainly muons back-scattered from ground. We have estimated this flux using the ground level measurement of upward directed atmospheric muons [21] being 3×10^{-6} cm^{-2} sr^{-1} day^{-1} which results in 3×10^{-3} “fake” events per observation night within the field of view of ASTRI-like. Comparing this with the 5000 muons/night expected to hit the telescope mirror, we can conclude that the proposed system is affected by a negligible background.

4. A possible configuration

The new IACT will be ASTRI-like, i.e. with a double mirror optics and multi-pixel focal plane consisting of SiPMs. However, it will be

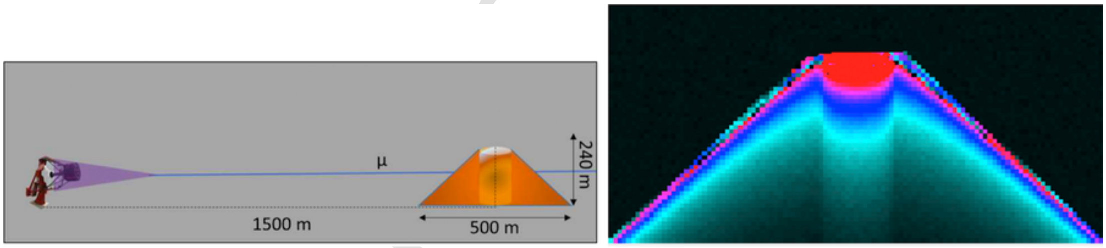

Fig. 3. Left: sketch of the telescope-volcano configuration used for our simulations. Despite Cherenkov light is produced along the whole muon path, we show only the one useful for our ASTRI-like telescope, i.e. that produced in the last 100 m. Right: a hollow conduit of 100 m diameter is resolved in about 9 nights by the muon radiography performed with the ASTRI-like telescope.

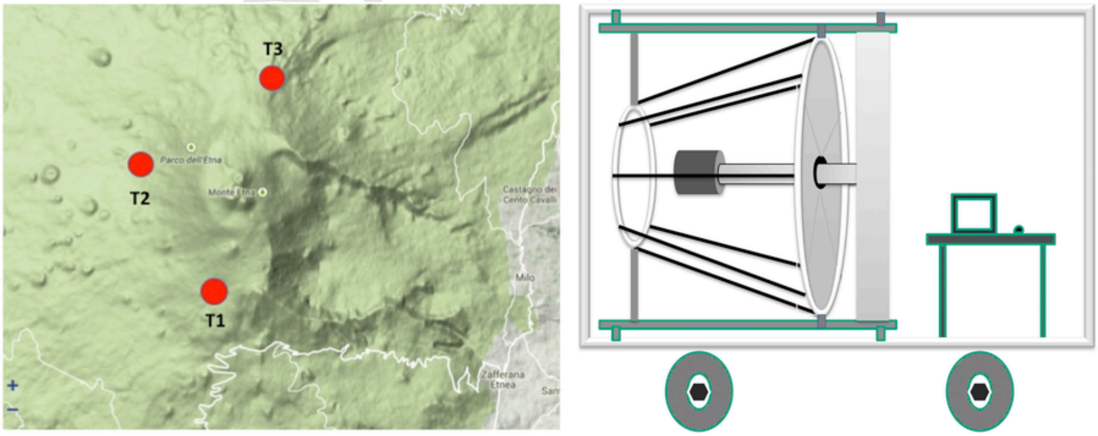

Fig. 4. Left: a possible configuration of the three different positions of the telescope around the SE crater to perform the Mt. Etna tomography. Right: sketch of a possible instrumentation.

smaller, lighter (about 200 kg) and lower-cost (roughly 150 keuro) compared to the current experiment at high sensitivity [5]. A possible configuration could involve a focal plane made up of 16 photon detection modules of 8×8 SiPM pixels (each module of 57 mm×57 mm ×30 mm). The primary mirror would consist of 8 hexagonal facets (aperture 2.1 m) while the secondary mirror could be monolithic (0.8 m aperture). In this configuration the FOV is 12° and the structure will not require any complex pointing system as the IACTs realised for the γ-ray astrophysics.

Multiple radiographic images (tomography), taken from different positions (see Fig. 4, left), could be combined to obtain 3D-images of the region of interest. Tomography can resolve the exact position of the density anomaly and its shape. We plan to mount the instrumentation on vehicles equipped with solar panels. Hence, it will be easy to set the instrumentation in the installation site and move it to another position, once the desired acquisition time has been reached (Fig. 4, right).

5. Conclusion

Our simulations show that:

- IACTs are able to perform muon radiography of volcanoes with a good spatial resolution;
- IACTs are not significantly affected by background noise, as telescopes based on different detection techniques;
- ASTRI could be used to test the proposed technology;
- the proposed technique allows a tenfold increase in sensitivity [20], with respect to another technique previously employed at Mt Etna [6];
- the proposed Cherenkov telescope is low cost, relatively light and can be easily moved between different installation sites;
- tomographic images can be obtained by combining the muon data from different installation sites around the volcano.

Motivated by these findings, a design of the telescope prototype is in progress and an international patent has been registered on 2016 December 1 (PCT/IB2016/056937).

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